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This Month—

Front Cover

A view of the 287-kv transmission line from Boulder Dam to Los Angeles, at the point where it crosses the Cronise Valley, Mojave Desert, about 200 miles from Los Angeles. These towers, each carrying a single 3-conductor circuit, are spaced about 1,000 ft apart. The distance between the 2 tower lines is about 300 ft, and the spacing between the 2 outer conductors on a given tower is about 65 ft.

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Mr. Institute Member:

Even though we have been "bumped" from the inside front cover we are still talking about membership from farther inside. And you can know more about membership from the inside, too, if you read Mr. Meyer's very fine story of the budget in the March number of ELECTRICAL ENGINEERING. Read it and get that membershippy feeling; then help your Section membership committee by sending in the names of those you feel should be invited to join the Institute. Do it now.

Everett S. Lee

Chairman National Membership Committee

Electric Discharges in Gases—III

Self-Maintained Discharges

By J. SLEPIAN
FELLOW A.I.E.E.

R. C. MASON
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In the light of basic processes discussed in the 2 previous articles of this group, this article reviews some facts and current theories concerning the various classes of self-maintained electric discharges in gases. This is the concluding article of a group of 3 devoted to the general subject of electric discharges in gases, the 2 previous articles having reviewed current knowledge concerning ionization and excitation, and ions in dense gases, respectively; it is the fifth of a series of special articles developed under the sponsorship of the A.I.E.E. committee on education, for full details concerning which see p. 238 of ELECTRICAL ENGINEERING for February 1934.—Editor

WHEN the gaseous space between a pair of electrodes conducts electricity under the influence of an applied voltage alone, without any external ionizing agent contributing to any important extent to the production or introduction of ions within the space, a *self-maintained* discharge exists. Though often external agents are necessary to initiate a current, after the discharge is established it itself continues to produce ions as fast as they are removed at the electrodes or lost at the discharge boundaries. If only electrons are active in producing ions, then a self-maintained discharge cannot exist; current flows only as long as an external source produces some primary ions. Discharges of this type often are called Townsend discharges.

Instead of considering all the possible ways in which other ionizing agents may contribute to the establishment of a self-maintained discharge, discussed by Dr. Karl K. Darrow at the close of the previous article of this group (published in the March issue of ELECTRICAL ENGINEERING, p. 388–95), we shall follow Townsend's original suggestion that positive ions produce new ions within the gas by ionization by collision, for simplification and because many experimental observations may easily be explained thereby. Thus the production of ions may be described through the statistical quantities: β_2, the number of new ion pairs produced by an electron in traveling one centimeter in the direction of the electric field; and β, the number of new ion pairs produced by a positive ion. If ions are lost only by giving up their charges to one electrode or the other, then the physical condition for a self-maintained discharge is this: that the total number of positive ions produced by an electron in moving from cathode to anode must regenerate one electron by the time those positive ions reach the cathode. Townsend put the condition in mathematical form, for uniform electric fields, as

$$\beta_2 = \beta \epsilon^{(\beta_2 - \beta) l} \qquad (1)$$

where l is the separation of the electrodes. For nonuniform fields β_2 and β vary from place to place, so an integral relation must be satisfied,

$$1 = \int_0^l \beta_2 \epsilon^{-\int_0^s (\beta_2 - \beta) ds} ds \qquad (2)$$

Equations 1 and 2 give the conditions under which the discharge just maintains itself. If the conditions are such that smaller values of β_2 and β obtain so that the "=" sign becomes a ">" sign, then the ions are not generated as fast as they are carried to the electrodes, the ions disappear, and the discharge stops. If larger values of β_2 and β obtain, such as to make the "=" sign becomes a "<" sign, then the ionization increases, and the current will increase if the field is kept constant.

Another simple type of self-maintained discharge may be obtained if the positive ions produce no ions within the gas, but free electrons upon their impact on the cathode. This activity of the positive ions, first suggested by Thomson, may be described by γ, the number of electrons liberated per positive ion impact; the resulting condition for a self-maintained discharge is

$$\frac{1 + \gamma}{\gamma} = \epsilon^{\beta_2 l} \qquad (3)$$

and a corresponding equation for nonuniform fields. A direct discrimination between the 2 ways of ionization by positive ions is not possible. The conditions for meeting eq 1, however, depend only on the nature of the gas, while those for eq 3 depend both upon the gas and upon the cathode material. Under some conditions at least, particularly those existing at the cathode of a glow discharge, the latter statement of the positive ion activity appears to be more nearly true.

SPARKING

As the previous articles in this series have discussed, the ionizing ability of electrons and positive ions depends upon the energy they possess, which is a function of E/p, while the number of collisions made varies directly with the pressure. Consequently, from the definition of the quantities we

should expect the functional relationships to be

$$\frac{\beta_2}{p} = f\left(\frac{E}{p}\right), \quad \frac{\beta}{p} = g\left(\frac{E}{p}\right), \quad \text{and } \gamma = h\left(\frac{E}{p}\right) \tag{4}$$

where each of the functions, f, g, h increase as their arguments increase.

Now suppose that voltage is applied between 2 electrodes in a gas, and that there is so little ionization in the space that the field is undistorted by space charge, so that the gradient E at each point may be determined from the applied potential by usual electrostatic principles. At each point, E determines the values of β_2, β, and γ by eqs 4. As the applied potential is increased, E at the various points of space increases, and with it β_2, β, and γ. When the applied potential is small, the inequality sign, $>$, replaces the "=" sign in the eqs 1, 2, or 3 and any ionization that may be in the space will not increase, but on the contrary will decrease in amount, so that the voltage will be borne by the electrodes without the development of large currents. If, however, the applied potential is large, then the "=" sign in eqs 1, 2, or 3 becomes a "$<$" sign, and any ionization in the space increases in amount, and the current increases as long as the field is applied. The potential that just causes eqs 1, 2, or 3 to be satisfied is called the *sparking potential*, and is the potential at which considerable current begins to flow between the electrodes. If the electrodes are large planes so that the field is a uniform one, then the gradient E corresponding to the sparking potential is called the *sparking gradient*. When the field is not uniform, the maximum gradient in the field corresponding to the sparking potential frequently is called the sparking gradient.

When the sparking potential is exceeded, the ionization quickly grows to such magnitude that the electric field becomes distorted, and new ionizing agents may make their appearance. The discharge changes quickly to one of the forms discussed later in this article—corona, glow, or arc.

Sparking Gradient. The condition for a self-maintained discharge in a uniform field, eq 1, may be transformed to

$$\frac{\beta_2}{p} = \frac{\beta}{p}\,\epsilon^{\left(\frac{\beta_2}{p} - \frac{\beta}{p}\right)pl} \tag{5}$$

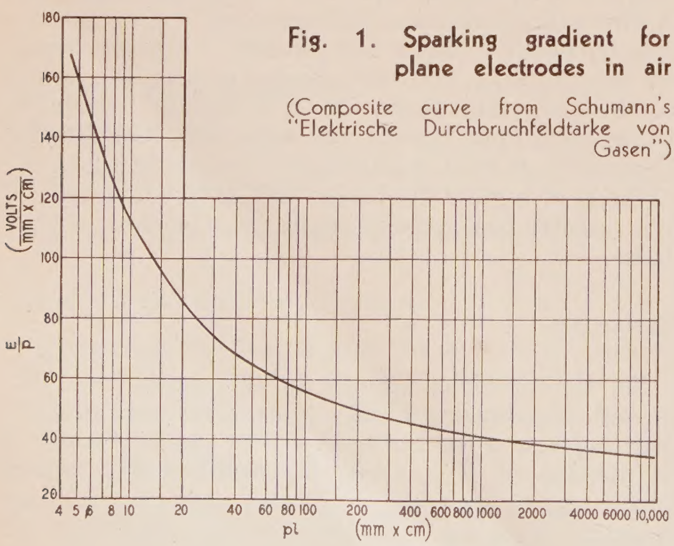


Fig. 1. Sparking gradient for plane electrodes in air

(Composite curve from Schumann's "Elektrische Durchbruchfeldtarke von Gasen")

Substitution of eq 4 in eq 5, shows that for sparking

$$\frac{E}{p} = F_1(pl) \tag{6}$$

An experimentally obtained curve is given in Fig. 1. The sparking gradient is not a constant, but is a function of electrode spacing and pressure. It commonly is stated that the sparking gradient for air at atmospheric pressure is 30 kv per centimeter. One sees, however, that this is only approximately true, and that wide departures may occur, for electrode separations often found in engineering practice.

Sparking Potential. From Fig. 1, one might construct a sparking potential curve, merely by multiplying the ordinate for any abscissa by that abscissa, for

$$\frac{E}{p}\cdot pl = F_1(pl)\cdot pl \quad \text{or} \quad El = V = F_2(pl) \tag{7}$$

Experimental curves for air, over 2 ranges of pl, are given in Fig. 2. The most striking feature is the definite minimum in the curve, with the rising branch for small values of pl, which results from the shape of the sparking gradient curve. One may account for the high values of V for low values of pl by the infrequency of collision of the ions in passage between the electrodes when pl is small.

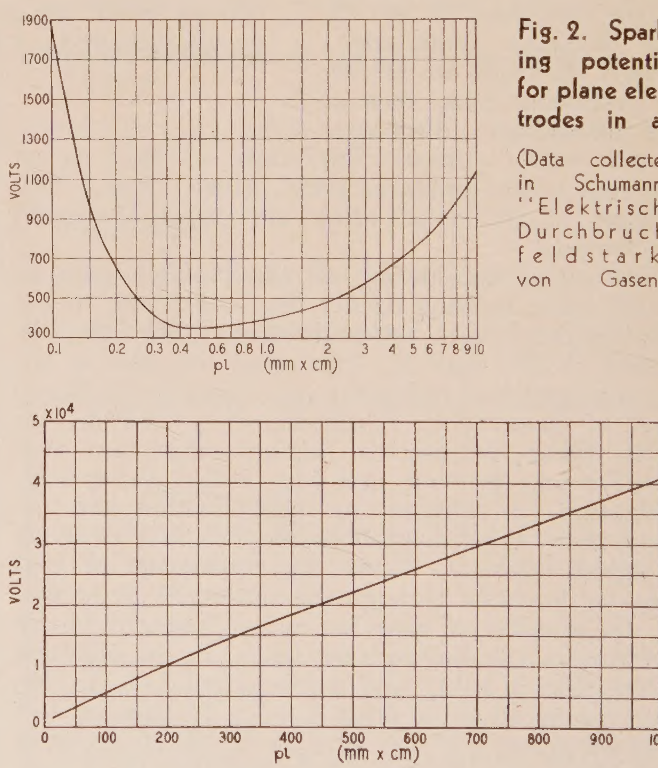


Fig. 2. Sparking potential for plane electrodes in air

(Data collected in Schumann's "Elektrische Durchbruchfeldstarke von Gasen")

The fact that V is a function of pl is expressed by Paschen's law: If the separation of plane electrodes is varied inversely as the gas density is changed, the sparking potential is unchanged. This is but a special case of the more general principle of similitude, which applies not only to sparking, but also to many parts of different discharge types: If all geometrical dimensions of a discharge space are

multiplied by k and the gas density is divided by k, then the same current flows with the same voltage applied. These 2 laws are very useful for transforming data obtained under one set of experimental conditions to other conditions.

Nonuniform Fields. An exact development of the criterion for sparking in nonuniform fields would be too extended for this space, but we can examine a qualitative explanation of the change in sparking potential when the geometry of the electrodes produces a nonuniform field. For simplicity, suppose the nonuniformity results from placing a grid midway between a pair of plane electrodes, all the potential being concentrated between one electrode and the grid, the field being zero from the grid to the other electrode. Now, if the conditions for a self-maintained discharge is met over the first space, ions may diffuse through the grid and carry the current through the second space. Thus, with the grid and the given field distortion, the sparking potential

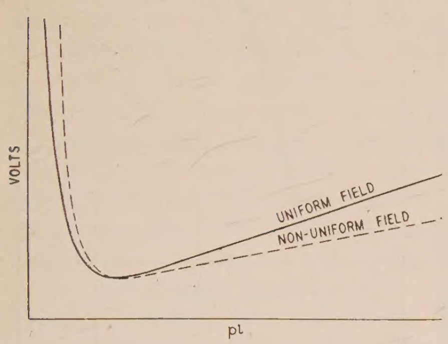


Fig. 3. Schematic representation of sparking potential in uniform and nonuniform fields

must be that for an electrode separation half the actual. For points to the right of the minimum on the V vs. pl curve, a reduction of effective electrode separation causes a decrease of sparking potential, while to the left of the minimum, a decrease of separation results in an increase of sparking potential. The effect in general of a nonuniform field, whatever the method of production, is different on the 2 sides of the minimum; to the left a nonuniform field *raises* and to the right *lowers* the sparking potential. A schematic representation is given in Fig. 3.

The voltage necessary to maintain a discharge with considerable current flowing differs from the sparking potential because of the development of *space charges*. When current flows, the electric field concentrates ions of one sign in front of the electrode of opposite sign; consequently, the field is distorted, being increased near the electrodes and reduced in the intermediate space. The effect is much larger at the cathode than at the anode, because the positive ions have much lower mobility than electrons. With the nonuniform field, the conditions, and the voltage, necessary for a self-maintained discharge are changed as discussed in the preceding paragraph. With increasing current, the space charges and resulting field distortions become larger, and the difference between the voltage necessary to maintain the current and the sparking potential grows. Since the effect is different on the 2 sides of the minimum on the V vs. pl curve, we have to the left a *rising* volt-ampere curve, and to right a *falling* characteristic, as sketched in Fig. 4. The latter, however, cannot fall below the minimum sparking potential.

The stability of the discharge depends upon the characteristics of the electrical circuit in which it is placed. The rising branch represents a discharge that is stable in any ordinary type of circuit. Any

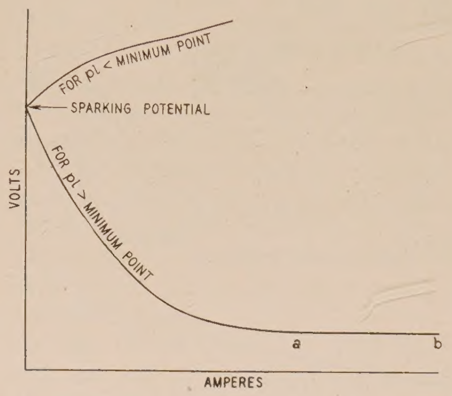


Fig. 4. Schematic representation of volt-ampere characteristics for low current discharges

point on the falling branch, however, may be obtained steadily in a d-c circuit only of the resistance in series with the discharge is larger than the slope of the volt-ampere curve at that point. For low resistances, as soon as the applied voltage is raised slightly above the sparking potential, the voltage falls discontinuously to the minimum voltage, and a current determined by the circuit conditions. In this case, "breakdown" occurs.

Thus, the "spark" or discharge which occurs when the sparking potential is applied, depends upon the characteristics of both the discharge space and the electrical supply circuit. Any of the 3 following types of discharge may result. Quite often, the electrical circuit is of limited continuous capacity, such as a charged condenser, so the discharge persists only for a short time; and in many cases, a "breakdown" occurs—large currents flow. Commonly, the term "spark" is used to apply to these cases of short time durations and large current discharges, in which a momentary flash of light accompanies the discharge, but there is no reason for making this distinction; such a discharge differs from an arc only in its transient nature. Perhaps the most common example is the lightning stroke, and on a smaller scale, the discharge of a condenser through a spark gap at atmospheric pressure.

Corona

The familiar faint bluish glow that surrounds a wire or sharp point to which a high voltage is applied, receives the particular name of *corona*. The small current characterizing corona results from the sharp radius of curvature of the conductor. The geometry of the electrode produces a nonuniform field. When the potential for a self-maintained discharge is applied and a small current flows, the resulting space charges, counteracting the effect of the curvature of the electrodes, tend to restore the uniformity of the field. At high pressures (atmospheric) a

more uniform field requires a higher voltage for maintenance of the discharge; thus, an increasing current requires an increasing applied voltage. The rising volt-ampere characteristic means that corona is a stable low current discharge, even in circuits of large capacity and low resistance. If the applied voltage and resulting current flow increases too far, the space

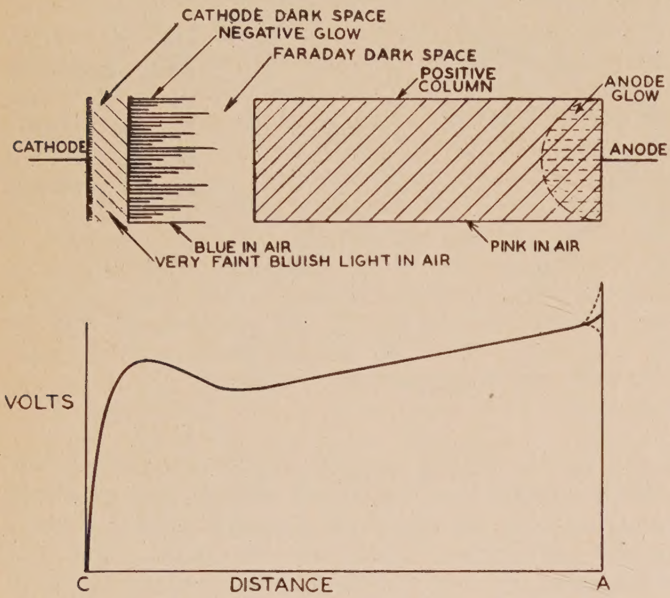


Fig. 5. Appearance, nomenclature, and potential distribution of a glow discharge

charges again distort the field, causing a lowering of the voltage necessary to maintain the discharge. Thus, above a certain current, the voltage required falls again; when this point is passed, "breakdown" may occur. The breakdown voltage may be considerably higher than the sparking potential, or corona voltage, at which current begins to flow.

Just as for plane electrodes, there is no critical gradient at the surface of the electrode at which corona starts; the corona gradient depends upon the curvature of the electrode. Both simple theory and empirical data give for the critical gradient at which corona forms on a negative wire in air at atmospheric pressure,

$$E_0 = 27.7 + \frac{9.53}{\sqrt{r_0}} \tag{8}$$

where r_0 is the radius of the wire in centimeters (the other electrode of lesser curvature is supposed to be remote) and E_0 is the gradient in kilovolts per centimeter at the surface of the wire.

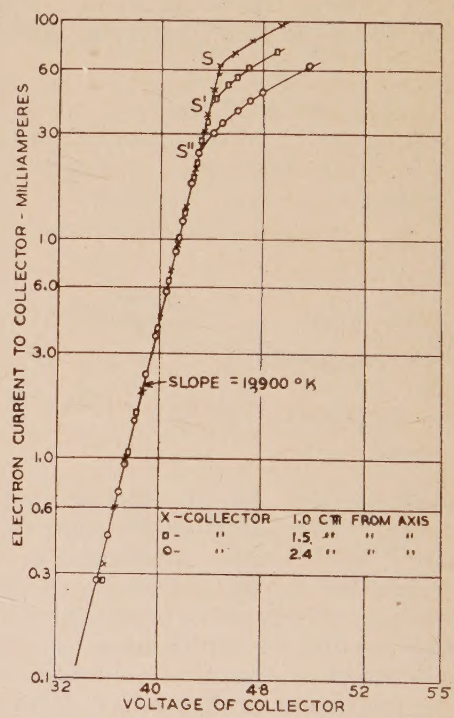
Glow Discharge

A self-maintained discharge, instigated by raising the potential applied to a pair of electrodes to the sparking potential, often takes the form of a glow discharge, as in the region *a-b* in Fig. 4. The appearance of a glow, with the color and shade of the main parts in air, together with the distribution of potential within the discharge is sketched in Fig. 5.

Cathode Region. The region next to the cathode—the cathode, or Crookes, dark space—is the part of the glow that is unique and essential. Most of the potential drop across the glow resides in the dark space. If the anode of the glow pictured in Fig. 5 were moved nearer to the cathode, some of the positive column would disappear without the rest of the discharge changing. If the anode approached progressively nearer and nearer to the cathode, the over-all voltage would change only slightly, until the anode reached the boundary of the cathode dark space. Then any further decrease in separation would demand a rapid increase in the voltage necessary to maintain the discharge. The evidence shows that the conditions for a self-maintained discharge must be met for the dark space. The discussion of the voltage necessary for maintenance of a current in the nonuniform field produced by space charges

Fig. 6. Current-voltage characteristic for a probe in mercury positive column

Arc current, 5 amp; pressure of mercury vapor, 7.13 baryes; tube diam, 6.2 cm; probe, 0.01 cm diam x 1.9 cm long, tungs, ten mounted parallel to tube axis (Killian, Phys. Rev., v. 35, p. 244, 1930)



showed that a voltage at least equal to the minimum sparking potential would be required. We identify 2 regimes for the glow discharge: the *normal glow*, in which the discharges does not completely cover the cathode, and the *abnormal* or *anomalous glow*, in which the cathode electrode is entirely covered.

For the normal glow, the voltage across the cathode dark space (the normal cathode fall, V_n), corresponds very closely to the minimum sparking potential for the gas and cathode material in use. The cathode fall is practically independent of pressure, but the thickness of the dark space, d_n, varies inversely with the pressure, in agreement with the principle of similitude. The cathode area covered by a normal glow grows or shrinks as the total current increases or decreases, so that always the current density remains constant. The normal current density, i_n, is directly proportional to the square of the gas pressure. We can write these conditions as $pd_n = C$ and $i_n = Dp^2$.

If the total current increases to such an extent that the entire exposed electrode area is covered, then the current density must increase above the normal value. The cathode dark space, being a region of space charge, must decrease in thickness; hence, by the analysis in the last section, the voltage required to maintain a discharge must increase: the abnormal cathode fall is larger than the normal, and increases with increasing current. The abnormal cathode drop also increases with decreasing pressure; an empirical relation is

$$V_a = E + \frac{F\sqrt{i_a}}{p} \tag{9}$$

The relation between pressure, current density, and dark space thickness in the anomalous case is given by

$$d_a = \frac{A}{p} + \frac{B}{\sqrt{i_a}} \tag{10}$$

also in agreement with the similitude principle.

A few values of normal cathode falls and constants appearing in the foregoing paragraphs are given in Table 1. As may be noted, the cathode fall is in general a few hundred volts. It is lowest with the alkali metals, and with the noble gases.

Negative Glow; Faraday Dark Space. At the sharp boundary of the relatively dark cathode fall space, a bright region, the negative glow, arises, and gradually fades into the Faraday dark space. The negative glow is a region of high ion density, within which a potential maximum exists. The concentration gradient of electrons is sufficient for diffusion against the opposing field to account for the passage of electrons toward the anode.

Positive Column. The positive column is independent of the phenomena at the cathode, so that really no distinction exists between the positive columns of glows and arcs, self-maintaining or non-self-maintaining. Since the glow is found more frequently at low pressures, in this section the low pressure positive column will be described, leaving the high pressure column to be discussed later in the section devoted to arcs. A distinctive feature of the low pressure positive column is that the discharge fills the whole of the section of the discharge tube.

A glow cannot exist with the applied voltage merely just equal to the voltage necessary to maintain a discharge in the cathode dark space. Some gradient, though usually small, is necessary in the positive column, because of losses of ions to the walls of the confining vessel. Since the walls are insulating, charge can be continually lost to them only if equal numbers of positive ions and electrons flow to the walls. Since the diffusion of the electrons is much faster than that of positive ions, the walls acquire a negative charge; a radial field opposing the motion of electrons and attracting positive ions establishes itself so that equal numbers of the 2 reach the walls in steady state. The walls of a discharge tube are negative by a few volts with respect to the axis of the tube.

The distribution of potential in the positive column, the ion density, and an important quantity—the electron temperature, Langmuir showed could be found from the study of the current collected with varying potentials applied to small probes placed in the discharge. The ratio of electron density at the surface of a probe bearing a potential V, negative with respect to the space around it, to the density remote from the probe is given by the Boltzmann relation

$$\frac{n_p}{n_g} = \epsilon^{\frac{eV}{kT_e}} \tag{11}$$

where T_e is the temperature of the electrons. Since the electron current flowing to the probe is proportional to the electron density at the probe, then the logarithm of the probe current will bear a linear relation to the probe potential (which may be measured with respect to any fixed point, the cathode, say, since only a constant will be added to V). In Fig. 6 are shown typical data illustrating the linearity. Equation 11 will hold only for *negative* potentials, so that a departure will occur at $V = 0$.

Table I—Normal Cathode Falls and Values of Various Constants for Several Cathode Materials in Different Gases

Cathode Material	Constants	Values of Constants in Different Gases: Air	O_2	N_2	H_2	He	Ne	Ar	Hg
Pt	V_n	277	364	216	276	160	152	131	340
	A		0.088		0.45				
	C				1.026				
	D		5.5×10^{-4}	3.83×10^{-4}	0.9×10^{-4}	0.11×10^{-4}	0.18×10^{-4}	1.41×10^{-4}	
Al	V_n	229	311	179	171	141	120	100	
	A		0.057		0.23				
	C		0.237	0.305	0.724	1.32	0.637	0.285	
	D		4.28×10^{-4}	1.39×10^{-4}	0.75×10^{-4}				
	E	230	290	230	144				
	F	105	78.5	107	255				
Fe	V_n	269	343	215	198	161		131	389
	A		0.085		0.34				
	C		0.311	0.419	0.9	1.66	0.722	0.356	
	D		3.01×10^{-4}		0.54×10^{-4}				
Cu	V_n	252		208	214	177		131	
	A				0.47				
	C				0.893				
Na	V_n			178	185	80	75		
K	V_n			170	94	59	68	64	
Hg	V_n			226	270	142			340
	C				0.89				

For all materials, B is approximately 0.004.
The units are: V_n in volts, current density in amperes per square centimeter, length in centimeter, pressure in millimeters of mercury.

Figure 6 shows a departure of the curve from a straight line at S; this marks the point at which $V = 0$ or where the probe is at the potential of the space around it. In this case, as the potentials are measured from the cathode, the space potential is 44.5 volts positive with respect to the cathode. The points S' and S'' give the space potential at points farther from the axis of the tube; the results show that the wall of the tube is negative with respect to the axis. Inspection of eq 11 shows also that the constant of proportionality between log i and V is e/kT_e, so from the slope of the curve of log i vs. V_e in Fig. 6 the electron temperature can be determined. As the probe current is directly proportional to the electron density and the square root of the electron temperature with a factor of proportionality given by the kinetic theory of gases, the current at space potential gives the density of electrons in the gas at once.

Experimental studies using Langmuir probes show electron temperatures from 5,000 to almost 100,000 deg K, while the gas temperature is a little, at the most a few hundred degrees, above room temperature. The explanation was given by Doctor Darrow in a previous article (*loc. cit.*). In general, the electron temperature decreases with increasing gas pressure. The electron temperatures are highest in noble gases. The electron density depends upon the current density, increasing nearly proportionally to the current; in many discharge tubes, the electron density is much less than 1 per cent of the gas molecule density.

Measurements of potential distribution show a constant low intensity field in the positive column, indicative of nearly equal average densities of electrons and positive ions. Since the loss of ions from the positive column is chiefly by diffusion to the tube walls, the ion loss increases as the tube radius decreases. The gradient increases too, in order to supply energy for the production of new ions to replace the ones lost. The gradient is thus inversely proportional to the tube radius. The gradient decreases somewhat with increasing current; it increases with increasing pressure. The changes are shown by curves in Fig. 7.

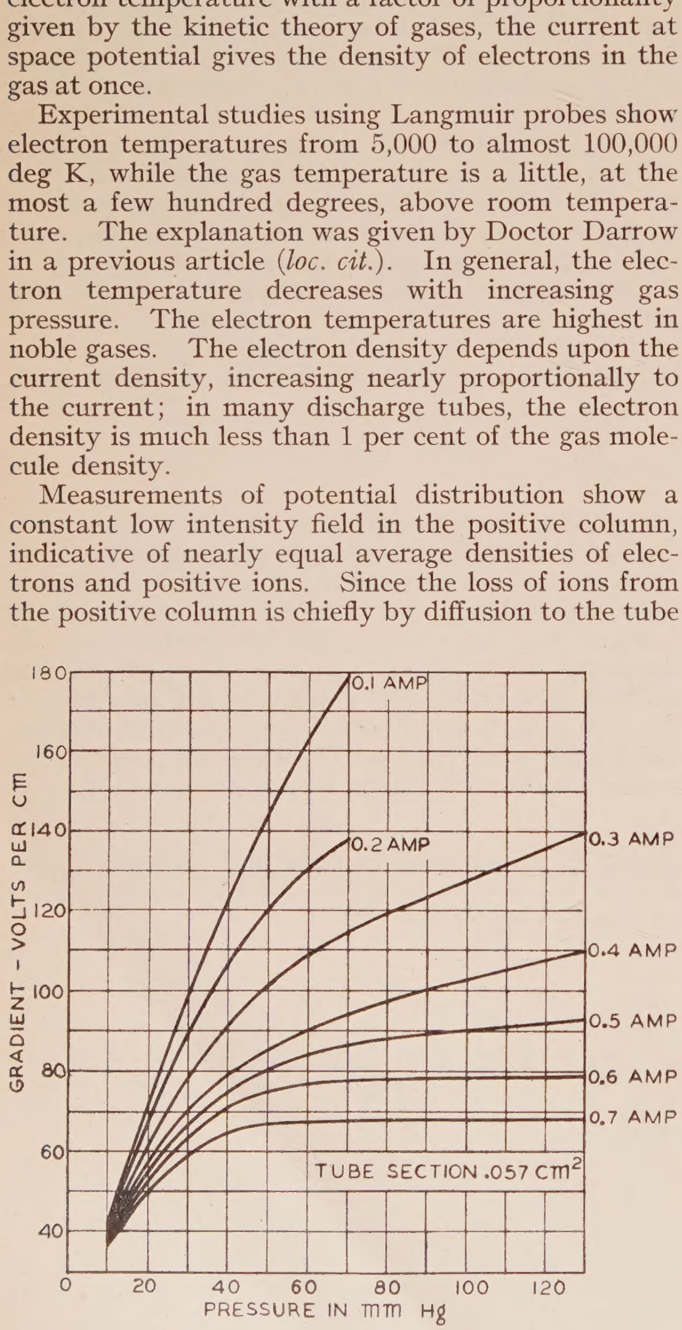


Fig. 7. Gradient of positive column in nitrogen as function of pressure for different currents

(From "Hand. der Experimentalphysik," after Matthies and Struck)

The production of new ions is probably chiefly through electron impact. In at least one case, Killian, from measured electron density and electron temperature, was able to calculate an ion production by electrons (using ionizing efficiency curves as given in the article by Dr. Lewi Tonks published in the February issue of ELECTRICAL ENGINEERING, p. 239–43) equal to measured ion losses to the walls.

In not all cases is the positive column and its gradient uniform; sometimes the column is broken up into regularly repeated bands or *striations* of alternate light and darkness. The heads of the bright regions, convex toward the cathode, are quite sharply defined and gradually shade off toward the anode into a dark region. The boundaries of the striations are equipotential surfaces, with a voltage difference between striations equal to an excitation or ionization potential of the gas. When examined stroboscopically, some apparently continuous positive columns are revealed to be made up of striations rapidly moving from anode to cathode.

The potential drop at the anode may be large, small, or even negative; it may or may not be accompanied by a visible glow or ball of light. This generalization may be made: the anode drop will be small, or negative, when the anode almost fills the tube; it will be large when the anode section is small compared to the tube.

Typical examples of the low pressure positive column may be seen in neon signs and mercury vapor lamps.

ARCS

Cathode Region. The arc is distinguished from the glow primarily by the phenomena at the cathode. The voltage drop at the cathode of an arc is only a few volts—usually of the order of the ionization potential of the active gas—which is small compared to that in a glow. Some new ionizing agent, not present in the glow and not considered in the previous discussion of the minimum voltage necessary for a self-maintained discharge, enters in the arc. One such agent, which is active at the cathode of some arcs such as those with carbon or tungsten cathodes, is thermionic emission of electrons. Electrons emitted from the cathode carry most of the current. Energy acquired in passing through the cathode fall of potential enable them to produce some new ions. The positive ions being attracted to the cathode impart to it the energy they have gained from the cathode drop and keep the cathode at a temperature high enough for thermionic emission. In this type of arc the cathode drop must be large enough for both of these functions.

In some arcs the cathodes do not reach a temperature high enough for thermionic emission; for

example, in the mercury pool arc the cathode temperature is probably only a few hundred degrees. For these, it was suggested by Langmuir that a very high intensity field existing at the cathode surface extracts electrons from the cold metal. Separate experiments show that fields of about 10^6 volts per centimeter are necessary to produce appreciable electron emission from materials at low temperature. In an arc, then, the cathode drop of only a few volts must be concentrated over such a short distance that a high intensity field exists at the cathode. The field is produced by the space charge of positive ions near the cathode, so the high field intensity necessary sets a lower limit on the positive ion current flowing to the cathode—a limit of about a 1,000 amp per square centimeter. In cold cathode arcs the total current density at the cathode is observed to be several thousand amperes per square centimeter.

Examples of the thermionic cathode arc may be seen in carbon arc lamps and in "sun lamps" with tungsten electrodes. Mercury pool arcs, iron welding arcs, arcs drawn by separating copper contacts, are all of the high intensity field type.

Positive Column. The positive column of the high pressure discharge distinguishes itself from the low pressure discharge in 2 features, which probably are connected: a definite section, and a high gas temperature. In contrast to the low pressure discharge, the high pressure positive column of an unconfined arc has relatively sharp boundaries; current flows only within a definite region, which expands and contracts with increases and decreases in current. The current density at atmospheric pressure is of the order of 100 amp per square centimeter.

The temperature of the gas in the high pressure positive column is high, also in contrast to the low pressure discharge. In arcs at atmospheric pressure, the gas temperature has been measured by 2 methods: (1) the absorption of X rays, α particles, or fast electrons gave the density from which the temperature was determined as the pressure was known; (2) the intensities of band spectra gave the relative population of certain excitation levels, from which, by means of the Boltzmann relation, the temperature was found. In fair agreement, the 2 methods give from 5,000 to 7,000 deg K for the arc temperature. As the electron temperature in low pressure discharges decreases rapidly with increasing pressure, it seems likely the electron temperature at atmospheric pressure is only a little higher than the gas temperature.

Though no bounding walls surround the positive column to which ions may diffuse and recombine, the cooler gases around the definite core of the discharge probably serve the same function. At the high temperature of the positive column, recombination of positive ions and electrons is negligible, but in the cool enveloping gas, recombination can take place. The chief loss of ions, then, is by diffusion to the boundary of the arc section, and recombination outside. Since the gas is at a high temperature, the positive column will lose energy by thermal conduction; probably a considerable part of the total is by this means. To overcome these 2 losses, energy must be put into the arc continually, through the intermediary of the electric field acting on the ions. The actual mechanism of ion production perhaps can be put under the heading of "thermal ionization," discussed by Dr. Tonks (*loc. cit.*).

The relation between current, arc voltage, and arc length often is expressed by an empirical equation (the so-called Ayrton equation)

$$V = a + bl + \frac{c + dl}{i} \tag{12}$$

where a, b, c, d are constants, and l is the arc length in centimeters. Different investigators find different values of the constants to make the equation fit their particular experimental conditions. In order to give some idea of the magnitudes involved, one set of constants out of the widely varying values reported is chosen:

Carbon in air	$a = 38.5$	$b = 2.15$	$c = 54$	$d = 6.1$
Copper in air	$a = 60$	$b = 11.8$	$c = 0$	$d = 35.5$

Over a limited range, Nottingham found the following relation for arcs of definite length between different electrode materials

$$V = A + \frac{B}{i^n} \qquad n = 2.6 \times 10^{-4}T \tag{13}$$

where T is the boiling point of the anode material. All results agree that both the total arc voltage and the gradient in the positive column (the coefficient of l in the Ayrton equation) decrease quite rapidly with increasing current for low currents, and approach a constant value for large currents.

Discharges With Separately Heated Cathodes. Though not truly self-maintaining, discharges with separately heated cathodes deserve mention because of their wide technical application. In these, a source of energy external to the discharge is used to maintain the activity of a thermionic cathode, usually an oxide coated filament of some kind. The gas pressure is usually low, so the negative glow and positive column are identical with those discussed under the glow. Commonly such discharges are called arcs, however, because of the low value of the cathode fall. Since the condition for a self-maintained discharge does not have to be met at the cathode, the cathode fall is much less than in the true glow. It is only necessary that the cathode fall be sufficient for the emitted electrons to produce positive ions necessary for the neutralization of the electron space charge. This requirement seems to be met in many cases by a cathode fall equal to the lowest excitation potential of the gas.

When the cathode filament emits electrons copiously, and usually when the cathode and anode are close together, the total voltage required may drop to a very low value—0.5 volt has been reported for sodium vapor, 1.7 volts for mercury, and 3.5 volts for helium. In these "abnormal low voltage arcs," close to the cathode the potential reaches a maximum at least equal to the lowest excitation potential, then falls again to the anode so that the over-all potential is quite low. Just as in the negative glow, a large concentration gradient carries electrons to the anode by diffusion against the opposing field.

Many grid-controlled gas-discharge tubes, such as those with the trade names "grid-glow tubes," "thyratrons" and similar devices, furnish examples of the independently heated cathode type of discharge at low pressure.

Bibliography

No attempt will be made to give references to original articles or to all the books covering this field, but a few are listed which will be valuable to those wishing to study the subject further:

1. Electricity in Gases by J. S. Townsend (Oxford Univ. Press) gives an account of the requirements for a discharge self-maintained by ionization by collision.

2. Elektrische Durchbruchfeldstarke von Gasen by W. O. Schumann (Springer) contains a complete and valuable summary of work on sparking gradients and sparking potentials up to 1923.

3. Der Elektrische Lichtbogen by A. Hagenbach (Akademische Verlag) contains a summary of older work on the characteristics of arcs.

4. The 2 German handbooks, Handbuch der Physik, v. 14 (Springer) and Handbuch der Experimentalphysik, v. 13, part 3, "Selbstandige Entladungen in Gases" (Akademische Verlag), in particular the latter, contain valuable résumés with complete references to original sources covering all types of self-maintained discharges.

5. The series of papers by Langmuir and Mott-Smith (*G. E. Review*, v. 27, 1924) develop the important Langmuir theory of probe characteristics, and apply the methods to the study of mercury arcs.

6. The last 5 chapters in Electrical Phenomena in Gases by K. K. Darrow (Williams & Wilkins) give a clear exposition of self-maintained discharges including arcs and glows, with many references to original work.

Industry Demands and Engineering Education

A study of the type of engineering graduate who will most satisfactorily meet the demands of industry and will be best adapted to present social conditions is contained in this paper. As a result of this analysis, changes in the type of college instruction now given are proposed. It is pointed out that the majority of students should be given a broad education which coördinates instruction in science, engineering, economics, and psychology, so as to fit the graduate for the managerial positions in industry; while a smaller group should be given specialized scientific and engineering instruction.

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AN ANALYSIS of prevailing conditions and opinions in this country shows 3 new and quite distinct aspects, when studied from the point of view of engineering practice and engineering education. The first of these is the idealistic concept that future engineering contributions must advance the standard of living and benefit mankind in his social relations. The second is that a large part of industry has become mechanized and requires a large staff of operators and managers which is now unsatisfactorily supplied from engineering graduates. The third is that industry requires only a relatively few highly trained engineers to do its diverse yet specialized technical engineering and research work. Add to these market demands the great expansion in fundamental scientific and engineering knowledge made in recent years together with the development of a high degree of specialization in each branch of industry and in each functional job in industry. This gives a perspective of the formidable and complicated problems now presented to engineers and to engineering educators. However difficult the task, it is necessary to take stock and to find out what may or may not be done to meet the new conditions.

The Social Side of Engineering

This country is reorganizing under an adversity-born movement to get a rationalized improvement in the conduct of its affairs. Under the impetus of this effort to bring about a new order, many believe that engineering becomes a major part of a planned economy whereby man becomes more fit and better able to control himself and his environment so that all his actions will benefit humanity as well as himself.

This is the idealistic concept that deranges many of our traditional ideas and practices. For example, our definition of pure science is very narrow; it is chiefly the gratification of man's inquisitiveness. It has no practical objective and no element of social well-being. It is an end in itself. Applied science or engineering is little different. Perhaps the greatest distinction is that engineering is always purposeful. It devotes itself to practical accomplishments in the realm of the material. It contains little conscious inclusion of the social or moral values that would be determined and weighed if an attempt were made to measure the effects of engineering contributions upon human welfare.

Thus both pure and applied science heretofore have stood detached from the social and moral aspects of man's career. In fact, it has been the ex-

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perience that this detachment, this selflessness, this objectiveness was essential to professional success. Despite universal agreement as to the greater importance of these aspects of man's career, the cultivation of the social, legal, and economic fields of life has been left to other professions in this age of specialization.

But the new conceptions and the new plans attempt to bring science and engineering to bear upon man's social life; to improve his conduct, to advance his standard of living and to control his environment. In summary, to make one complete engineering problem of all earthly issues and then to obtain a single humanitarian answer. This ideal calls for imagination of the highest order and invests science and engineering with the dignity, importance, and utility which they could never attain were they to remain either a purposeless prying into hidden things or were they pursued in the hope of securing only material results.

The depression-born reason for these new ideas lies in the fact that the merits of engineering and of the civilization for which it has been largely responsible are questioned. Engineers are on trial because of breakdowns for which they are held responsible. Moreover, even engineers agree that drastic changes are necessary in national affairs before recovery can or should be had. The nation apparently is justified in its skeptical attitude toward a future premised only upon a continuation of scientific and engineering contributions similar to those that have proved of doubtful social value in the past. It is apparently logical to say that a social purpose must be combined with a practical purpose in the engineering work of the future.

Leaders in science, in engineering and in technical education must take cognizance of these new ideas and either act to carry them out or to prove them to be fallacious. If the ideas are good, then the endeavor must be to make social science a part of engineering education and professional engineers must find and use social yardsticks to measure the value of their work. If the concept is accepted, new and very difficult problems will be encountered in engineering education and in engineering practice. Social sciences are not formulistic or calculable for the reason that they deal with human actions and emotions. At best they permit only the use of a statistical analysis and at worst they deal with only the social and moral averages of a mob of irrational human beings.

But the engineer, the scientist, and the educator are called upon to apply their scientific methods of analysis and their finite solutions to the social sciences; to apply the cool-headed objectiveness whereby they are accustomed to reach quantitative conclusions, and yet they must retain the intelligent emotion that is necessary to motivate all human action. It is true that the engineer is only another human being in the final analysis, and yet the world, in its dire need, commands him to become that ideal creation—the social engineer. This is the climax of liberal opinion and suggestion that has been reached through the accumulating pressure from many sources, which has heretofore been typified by that oft-repeated phrase "engineers should have more of the humanities in their courses."

The Idealistic Concept Is Fallacious

A thorough analysis of the origin of this social concept of engineering and of the difficulties that confront the profession in endeavoring to carry it out leads to the conclusions that the concept is erroneous and that its practical application is impossible. It is analogous to the splendid generalization that poets should write only poems that contribute to man's well-being or to advocate that all medical practitioners must also be public health officials. But it is unsafe to use these idealistic generalizations when dealing with specialized fields of training and practice. Experience, not theory, has dictated specialization. The humanitarian ideal of engineering takes into account neither the function of the engineer nor the practical requirements of both his educational and professional activities. The engineer can build a bridge to withstand a definite stress, but he cannot protect his bridge from breakdown if human beings load it beyond its design limits. This is the functional job of the policeman.

Nor can engineers admit that the present troubles of civilization came about because their contributions were not in the public interest. They claim, instead, that the troubles resulted from the incapacity of other national leaders to make correct adjustments between capital, labor, power and machinery and were essentially financial in character. The engineer can and should do his part to get present maladjustments corrected, but he must do this largely as a citizen and not as a professional man.

Viewed accurately, the engineer is but one of hundreds of similarly specialized functional operators in this civilization. He can coöperate with other citizens to perform his broader obligations to humanity, but he cannot, in his specialized education and practice, devote concentrated attention to the social and moral aspects of life and weigh his work on these scales. He cannot succeed in his profession and at the same time carry on a Messianic rôle in civilization.

Engineers as Business Men

But social ideals should not be dismissed from a less idealistic consideration because undoubtedly there are practicable opportunities to introduce training for men who are not specialized functional engineers that will enable them to advance our standards of living. These opportunities lie in the possibility for training better equipped men to staff industry in those positions that do not require specialized or professional engineers as functional technical workers. With the growth of the use of power, engineering equipment and engineering methods and the coagulation of industry into business enterprises that consist of a large assembly of men, money, equipment, and materials there has come about a demand for semi-technical men to operate, maintain, and manage these enterprises. These men do not perform specialized engineering functions, yet they use engineering knowledge in combination with other knowledge to do the required work. In all manufacture, in transportation, in communication,

in light and power supply, and in many other industries the operating staffs must be competent and trained men and it is very desirable that a large number of these men should have training in fundamental science and engineering as a part of their preparation for their duties.

These men are responsible for getting results from the aggregations of capital, labor, power, and machinery that go to make up business enterprises and they must bring to bear a broad yet specialized knowledge of their work because they must use and weigh many engineering, social, and economic values in making decisions or in conducting their parts of the business. They should know pure science, applied science, economics, banking, accounting, and psychology in order to succeed. They are the cogs and controllers in the business mechanism. The requirements for their adequate training are as diverse as their functional tasks in business, but they do not conform to the definition or to the functional specification of the professional engineer. They may well be called professional business men.

Occupational records of engineering graduates during recent years show that from 60 to 70 per cent of them are now engaged in this class of work. They start as testers, apprentices, helpers, clerks, maintenance men, and operators and advance along various paths to become heads of departments and managers. They do not use their technical tools nor their technical knowledge in any direct specialized applications after graduation, even though many of them bear the title of engineer. Even the chief engineers of large enterprises are more nearly business men than engineers because they have not been able to keep up their technical proficiency during the lapse of years and have devoted their talents to management with stress upon its economic and organization aspects.

At present this industrial market is supplied largely, but in hit-or-miss fashion, by the engineering schools. But this is only because these graduates approximate the specifications most closely. And an unfortunate feature of this situation is that the men are not properly trained and perform their work too frequently by over-stressing their engineering point of view and under-stressing the social and economic aspects of business. And even their technical competency should be challenged after the lapse of a few years. They have become rusty and out-of-date, but will not acknowledge this fact when technical matters are under consideration. A combination of pride in their former training, in their label of engineer and the egotism that accrues with position causes them to believe they are still competent technical engineers and that they can and should make technical decisions without consulting specialists. As a consequence many very bad engineering decisions have been made in all industry and millions of dollars have been wasted. This type of man cannot function as a business man as well as an engineer. As a corollary, undoubtedly these men, coming from engineering, are not adequately trained to perform the other duties required of their positions in industry. Possibly this is one reason for many present social and economic maladjustments—their decisions have been technical and not social in too many instances. Good engineers are seldom good managers of men; their training and their type of mind are against them in dealing with human beings.

But the significant fact is that engineering graduates are going into industry to supply this demand and the demand will increase as industry grows and becomes more technical. It is in this field that the large group of men must be trained, and it is this fact, together with the functional duties that these men must perform after graduation, that makes it possible to consider the development of an educational course that will include the humanities. This would afford these men a knowledge and a perspective that would enable them to advance our civilization as well as themselves.

The Day of the Specialist Is Here

Industry does not need and cannot use in strictly engineering functions the large number of engineering graduates produced each year by the technical schools. This fact must be faced by engineering educators. This decrease in the market demand for engineers has been accompanied by very greatly raised standards of proficiency in engineering training and a high degree of specialization in engineering practice. Specialists in dielectrics, in electronics, in thermodynamics, and in many other lines of engineering have developed their branches to such a degree that a jargon as well as a knowledge prevails in each field that is not known by engineers in other fields.

All engineering educators and practicing engineers feel the pressure that comes from the enormous increase in the fundamental but highly specialized scientific and engineering knowledge gained in recent years and this knowledge continues to increase. The educators also feel the pressure of the demands from the extremely diverse and yet highly specialized fields of engineering practice. So that the educators find it possible only to give the essentials of engineering and science and the engineer is forced to specialize in his work and study by the stress of competition.

One practicing engineer can be quoted by hundreds of others when he says: "I am forced to concentrate upon my own specialized field in all my studies and practice and even then I find it difficult to keep ahead of my brother specialists. I have no time to keep informed about any other fields of science or engineering or even in those occurring in my own branch of engineering. I am forced to specialize to succeed."

Another engineer speaks to the same point from a different angle when he says: "The specifications for an engineer stated by the Engineers' Council for Professional Development are utterly impracticable. Most of us must concentrate upon one specialized field of engineering in order to succeed; it is impossible for us to be informed broadly or to be competent in the universe of engineering under present competitive conditions. This is the day of necessary specialization in engineering and yet the E.C.P.D. is attempting to legislate generalization."

Thus, in the technical realm, the field demand is for a thorough scientific and engineering training so that technical graduates may be equipped to start out in any of the numerous specialized fields of in-

dustry for which functional engineers are required. In this education, specialization must be discarded for thorough but a broad general training in science and engineering because of time limitations.

The foregoing analysis indicates that the present demands from industry reduce to the possibilities of training 2 types of men: (1) a large number of men with a broad training that includes some fundamental engineering and science to fill the functional positions of a large part of industry; and (2) a small but very highly trained group of technical men who can be developed into technical specialists. The first group would supply the future executives of industry and must, if possible, have training that will enable them to advance our social as well as our material standards. The second group would supply the needs of industry for the professional engineer. What can or should the engineering schools do to supply these demands? Particularly when the present product fills neither specification satisfactorily and yet meets with little, if any, effective competition from the products of non-engineering schools.

These 2 demands already have influenced engineering education directly and indirectly. One engineering educator says: "We are preparing men for life and not for professional engineering." Another says: "We are preparing men for professional engineering. We are raising our technical standards and are concentrating upon the use of rigid mathematical studies of the fundamental sciences. We are discarding all so-called practical and applied engineering courses." These 2 extremes are reflected in some degree in all engineering schools. This is evident from the debates about the advisability of shop work, the widespread adoption of courses in administrative and industrial engineering and in the frequent addition of advanced work in mathematics and physics. Yet in very few instances have the schools faced these 2 demands honestly in order to satisfy them or to refuse them.

The Ideal Business Course

Based upon the market for men, the type of training required, the advancement of society, and the present competition, each engineering school can well afford to measure the possibilities for instituting a course that will prepare men for the business positions of industry. This course is broader than engineering and requires a new perspective together with a university type of faculty and facilities.

Since the Civil War, or, rather, since the growth of industry and of the professions, the chief attention of educators has been given to specialization. The professional schools were created, the business schools were created to teach economics and banking from the point of view of business, the agricultural colleges grew large and the engineering courses of the traditional type were instituted. This left as the general course for students with a nonspecialized objective only the arts course with its A.B. degree. If this was too general some students entered the engineering, business, or agricultural schools even though they did not propose to follow these occupations.

Viewed from the standpoint of preparation for life in the present industrial civilization, the traditional arts course is more inadequate and more highly specialized than the engineering course. The mass of young men who graduate from engineering, arts, science departments, and economic departments enter upon a business career. Yet none of these courses is balanced as to content, coördinated in teaching, or operated to give a preparation for a business life. Specializing in languages, literature, or history is analogous to specializing in civil or electrical engineering as a preparation for life. The specialization is a matter of direction only. From the point of view of industry and of this type of student there is an unbalance in course content and a lack of purpose and viewpoint in the teaching.

Why not make a new course that incorporates the best elements of both the engineering and arts courses to prepare the large majority of college students for business life and relegate both the older courses to more highly specialized types of education? This new course would prepare men for life as interpreted by the occupational positions of industry and commerce. The base of such a course would be science, applied science, economics, and psychology, with electives in the humanities, in accounting, in banking, and in business law. Such a course should be taught by teachers who have been trained in the use of scientific methods so common to engineering, who are familiar with the equipment and operations of industry and who are broad enough to introduce and use humanitarian criteria in their educational measurements of value.

It is evident that the present courses in administrative or industrial engineering do not measure up to the requirements and possibilities of the proposed course, although they attempt to do this in some degree. These courses are unsatisfactory because present faculties in engineering and arts are like water and oil. They do not mix. In some instances the economics department dominates and in others the engineering department keeps control. There is a lack of unity, perspective, and coördination in developing and teaching these courses. The engineering instructors attempt to teach orthodox engineering as taught to technical students and use the technical point of view in teaching and then the economics instructors teach orthodox economics as given to arts students who specialize in the subject and use the academic point of view in their teaching. The usual result is either failure or a dominance by one department with a consequent unbalanced and inadequate training for the students.

Educators with the proper viewpoint and training can develop an adequate course for these students. It must be devised to train men to apply the principles of science and engineering to business and industry and yet must incorporate that other type of training that will enable these men to direct other men and to produce business results and those that will, in some measure at least, contribute to man's welfare. These men can be taught to use and control dollars, machinery, men, and power so that a social as well as an economic balance will prevail in their business enterprises. Their course should not be narrow or restricted so that a student could enter

either a specialized engineering or arts course readily if he has the desire and his capacity points in that direction.

The course proposed would find its chief present handicap in finding competent teachers—with knowledge, with point of view, and with courage to enter upon uncharted courses. Essentially the base for the student body, the faculty, and the course content must come from the engineering and economics departments, with accent on the engineering method and point of view. The course must be a welded whole and not a composite of courses already given in the 2 departments. It must have a content, a method, an administration, and an identity of its own to be successful. It should be a separate college in the typical university organization.

Or an Ideal Technical Course

An equally radical approach to technical engineering education is indicated if the schools wish to supply the elevated technical demands of industry. The number of engineering students must be reduced more than 50 per cent and the courses must be changed in content and raised greatly in their technical standards. Extreme specialization in either theory or practice is impracticable in engineering education and thus students must be trained to enter upon a career in any technical field. Only fundamental scientific and technical subjects can or should be taught. Since recorded knowledge in science and engineering is now so voluminous, all instructional time must be devoted to the intellectual advancement of the student and this necessitates the elimination of routine, practice, or informational courses.

Rigid treatment by the use of mathematics must be applied to the fundamental sciences to form the foundation for such a training and the course must be taught with a method and from a point of view that will develop initiative and adaptability for creative intellectual effort if it is to be successful. Undoubtedly the present engineering courses should be scrutinized closely and changed to conform to the new requirements and standards. Routine drawing and lettering, shop work to develop manual dexterity, laboratory work of the ordinary routine testing type, applied courses such as bridges, power, transportation, and even the present differentiation between civil, electrical, mechanical, and chemical engineering courses—all these must be weighed, changed, or discarded. In addition it might be advisable to weld together the pure science courses and the engineering courses to form one college in the typical university organization.

Because of the high standards demanded, the lack of time, the volume of fundamental knowledge and the educational goals that are sought, each lecture, each experiment, and each lesson must be checked to determine its essential value in the course and the part it plays in completing the training desired. Undoubtedly a mathematical approach must be used because of its time-saving attributes and because of its quantitative conclusiveness. Yet the basic principles of pedagogy must not be violated if this method and this type of course are to be taught successfully and are to be used to train men for specialized engineering and research.

It should not be forgotten that an engineer is more than a pure scientist; he must be able to apply his knowledge to get practical results. Some degree of technique and manual dexterity is desirable and should be taught, but this element should be an incidental contribution obtained indirectly from the more fundamental intellectual training. It must also be granted that less rather than more time can be devoted to nontechnical subjects, however desirable they may be. Perhaps an adaptation and concentration of the nontechnical subjects are also feasible so that the time spent on these courses will produce better results than are had at present.

An essential part of this conception of a technical course is a careful selection of the students and the instructors. They must be high in quality although relatively few in number and their capacities must be measured by technical yardsticks. Undoubtedly the student selective process should be introduced in his preparatory schools. Another essential of the instructional staff is practical experience and the ability to arouse the interest of students and to stimulate them to creative effort. Despite obvious difficulties, this type of course with an adequate follow-up after graduation appears best suited to supply the research men and the technical men who are needed in industry—men who will truly practice professional engineering.

Conclusion

If engineering educators agree to follow the demands of industry, the specifications for the 2 types of courses to give are as follows:

Course No. 1. A course for the mass of students that is based upon a broad education developed largely from science, engineering, and economics and taught chiefly by teachers using engineering methods and having both business and engineering knowledge, so as to train men to staff and operate mechanized industry.

Course No. 2. A course with very high standards in science and engineering to be taught by scientific and engineering specialists to be given a selected number of students so as to train men to supply the specialized technical needs of industry—the future professional engineers.

Undoubtedly some schools can and should develop both of these courses, but a large number of schools will find it wiser to offer only one of these courses. Since the demand for the greatest number of men is filled by course No. 1 and since only a small number of men are needed by industry from course No. 2 the indications are that a majority decision will favor course No. 1. Moreover, only a few schools can obtain and sustain the faculty and facilities needed to carry out the objectives of course No. 2, while most of the schools could readily adapt themselves to the specifications for course No. 1.

To be successful in completely meeting industry demands, it would be necessary to make a complete revision of the typical university organization and to form a separate college for course No. 1 and another college for course No. 2. This, of course, would involve a radical change of the present university organizations and would require recombination of the existing colleges and courses.

The Present Theory of Electric Conduction

The present theory of electric conduction in solid conductors and semiconductors is reviewed here by a recognized authority who interprets some of the results of modern physical research in the light of their bearing upon the theory of electric conductivity. First the author gives a short review of the present theory, then discusses the breakdown of ionic crystals, the quantum theory, and cold discharge phenomena.—Editor

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THE ELECTRON THEORY of conduction in metals was developed qualitatively about 1900 by Lorentz, Riecke, and Drude. They assumed the presence of free electrons which are accelerated in an electric field, but which lose by collisions with the atoms of the solid the additional energy that they have gained in excess of their average thermal energy. This lost kinetic energy appears in the form of Joule's heat. A quantitative development of this theory leads to the conclusion that the conductivity should be proportional both to the number of electrons per cubic centimeter and to the mean free path (that is, the distance over which an electron can travel on the average without losing its velocity) and also inversely proportional to the average thermal velocity. The same mechanism accounts for heat conduction; inasmuch as electrons of greater velocity would move to regions of low temperature or lower velocity. The high point in the theory is the deduction of the law of Wiedemann-Franz which states that the ratio between thermal and electrical conductivity for any substance should be equal to a universal constant multiplied by the temperature. This electron theory also accounts qualitatively for thermoelectric effects, the Hall effect, and similar phenomena. However, difficulties arose, the most important of which was the interpretation of the operations on the specific heat of metals. If, as was assumed, the electrons behave like gas molecules, as they should according to classical statistical mechanics, it also would follow that the electrons must have the same specific heat as gas molecules. However, the measured specific heats of metals led to the conclusion that only the atoms of the metal can contribute to the observed thermal energy, and that the electrons possess little or no thermal energy. From these considerations it would follow either that the number of free electrons is very small and, to account for the observed conductivity, it would be necessary to assume large mean free paths for the electrons, or that one would have to take the energy of the electrons independent of the temperature. This, evidently, left the Wiedemann-Franz law without a theoretical basis. There were other difficulties also which will be mentioned subsequently. A logical interpretation came with the application of the new quantum theory to free electrons by Fermi,[1] Pauli,[2] and Sommerfeld.[3] Only the conclusions of these investigators[4] will be given first; more details will be referred to later in the article.

Sommerfeld showed that although free electrons are present in large numbers (about one or more per atom) and possess very high average velocities, these velocities should be almost independent of the temperature. Consequently the contribution of the electrons to the specific heat would practically disappear. Thus according to classical theory the average thermal energy at room temperature; expressed in the usual notation (if e is the charge on an electron, an energy of V volts is an abbreviation for energy equal to eV), would be about $^1/_{25}$ of a volt whereas on the basis of the new theory this would be about 5 or 10 volts. However, in spite of the negligible specific heat, the Wiedemann-Franz law is found to be valid because the smaller variation with temperature is compensated for by a larger transport velocity. Furthermore, the experimental result that the resistance at room temperature is about proportional to the temperature could not be explained on the basis of the old theory without special assumptions. But this follows directly from the calculation of the interaction of electrons with the vibrations in the crystal lattice of the metal, as shown by Houston and others.[5]

The new theory also clears another difficulty. According to the old theory, if a temperature gradient is set up in an isolated metal rod, a potential difference should be set up. However, this could not be found experimentally, and this failure is explained by the new theory.[6] Because of the practical independence of the temperature of the electron pressure in the metal, a much smaller potential difference is necessary to compensate for a temperature gradient. The optical properties of metals are under investigation at present—experimentally by Professor Wood, and theoretically by Kronig, Peierls, and others.[7]

Insulating crystals have been shown to be insulating not because electrons cannot move freely between the atoms of the crystal lattice, but because these lattices contain no free electrons.[8] This has been demonstrated by the experimental work of Gudden and Pohl, who generated electrons inside of rock salt, diamonds, and zinc blend by illuminating the crystals (photoelectrical effect), showing that these electrons could move freely through the crystal lattice. The new quantum theory has helped us

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here to a deeper understanding of the difference between metals and crystals, i. e., between "free" and "bound" electrons. Even the free electrons are subject to the forces originating in the ions of the metal lattice, and further investigation is necessary to determine the boundary line, as will be reported later. In addition to this electronic conduction, typical ionic crystals—crystals built of positive and negative ions (like rock salt)—have an electrolytic conduction. In this case the ions themselves move as in a liquid solution, and as a result there occurs a decomposition of the crystals with deposition of the products at the electrodes. The mobility of the ions, and, as a result, the conductivity, increases very rapidly with the temperature (proportional to $e - Q/RT$). As has been shown especially by the investigations of Tubandt,[9] the mobilities of the 2 ions of opposite sign are very different; practically only one type migrates. As to which ion possesses the greater mobility depends upon the crystal, and no complete theory of this phenomenon as yet has been suggested.

Semiconductors (oxides and sulphides) have been investigated theoretically by Fowler and Wilson of the University of Cambridge with the help of the mathematical relations of the new quantum theory.[10] Practically, conduction electrons can be set free in sufficient number only from impurities present to a small extent. In this respect the deductions of Fowler and Wilson confirm older calculations. Based upon this point of view there exists a dissociation equilibrium between the atoms of impurity and their dissociated products (free electrons and positive ions); then the free electrons set free by this dissociation move through the lattice of the crystal.

Breakdown of Ionic Crystals

Ionic crystals constitute one of the simplest forms of solid matter and therefore investigations of their electrical breakdown promises to lead to a deeper understanding of this phenomenon. Such investigations have been made recently. However, before the conclusions of these investigations are outlined, the theories that have been developed for the breakdown in solids will be enumerated.

There is, firstly, the theory of the thermal breakdown developed by Wagner and Rogowski,[11] according to which a rise in temperature produced by the current passing during an initial period, is responsible for the effect. In solids, this current would cause fusion or carbonization in a narrow path, followed by conduction in the channels thus formed. In liquids, formation of vapor followed by a gas discharge through this vapor would result. In gases, the corresponding process is the thermal ionization of the gas and electron emission from the hot cathode, which is characteristic of the arc. While it seems obvious that these processes occur, they are not the elementary processes. They are more important in alternating current discharges than in the case of a single voltage pulse because a certain time is needed for the initial current to heat the material sufficiently.

Secondly, there is the theory of ionization by collision which has been developed by Townsend[12] especially for gases. This theory may be described briefly as follows: In the gas between the electrodes some ions and electrons always are present, due to traces of radioactive material, to cosmic rays, or to some similar source of radiation. If an electric field of sufficient strength is applied these electrons are accelerated. In colliding with gas molecules they will lose part of the velocity gained in the electric field, but if the field is sufficiently high, or the gas pressure sufficiently low so that collisions are rare, they may be enabled to accumulate an energy sufficient to ionize the gas molecules (between 10 and 20 volts). They produce new electrons which in turn are accelerated and move toward the anode, and ionize in turn. In that way the process of progressive ionization or an electron "avalanche" is built up toward the anode.

Everything would be over with this one avalanche, however, if it were not possible to generate at the cathode an increasing supply of electrons. According to Townsend's original theory this was accomplished by the positive ions that are generated in the ionization process and driven toward the cathode. It was assumed that these ions either ionized the gas at the cathode by collision, or extracted electrons from the metal, a process that is known to occur at high field strengths. A difficulty in this theory seemed to turn up, however, when experiments of Rogowsky[11] proved that it took only 10^{-8} sec to start the discharge, a time wholly insufficient for the heavy ions to reach the cathode. Franck and Hippel[13] showed, however, that this difficulty could be overcome by taking into account the space charge phenomenon which arises in the process. In the first electron avalanche the electrons which are swept away leave behind the positive ions which built up a space charge around the anode, diminishing the potential drop close to the anode, and increasing it accordingly in the neighborhood of the cathode. A few successive electron avalanches concentrate the whole potential drop directly in front of the cathode, resulting in a field intensity so high that electrons are extracted directly from the cathode in what is known as a cold field discharge, which will be discussed subsequently. As only the motion of electrons is involved, the time difficulty does not occur here. Some time later, of course, the positive ions do reach the cathode and establish then the normal cathode drop.

Experimental proofs of this idea can be found in recent experiments by Hamos, Marx, and Steenbeck[14] who, with the help of a Kerr cell used as an optical shutter, found that in the first 10^{-7} sec the luminous discharge grows out from the anode toward the cathode; they therefore conclude that the luminous region is the region in which space charge occurs.

Joffe,[15] and with him the Russian School, have interpreted the breakdown in crystals as being caused by a process in which some ions, which have been loosened in the lattice structure, are accelerated sufficiently to ionize by collision (tear loose other ions or eject electrons from them). Recent experiments of Hippel, however, are intended to disprove this view.[16] Hippel's experiments were made with sim-

ple crystals. His experimental advance arises from the fact that by short circuiting the discharge through a vacuum tube as soon as it has started, he avoids the subsequent destruction of the path of the first discharges. Thus it is possible to see the path of the first discharge in the crystal, which under usual conditions would be destroyed by the strong current that sets in after the breakdown. Hippel uses polished electrodes (not points) and is careful to avoid the edge effect. He finds that under these conditions there is always a fine channel starting out from the anode, which branches into several channels going in the direction of the cathode. This form occurs in the same general manner, both for sodium chloride and barium sulphate, in spite of the fact that the electrolytic conduction is carried on in the former by the positive sodium ions and in the latter by the negative sulphate ions. From this it is concluded by Hippel that it is not the ions, but the electrons originally present in the crystal (produced through either one of the effects mentioned before for gases, or through a photo-effect) that are responsible for ionization through collision.

The mechanism of the process is as follows: An electron, originally present and accelerated through the field in the first instant, starts to ionize on its path to the anode and leaves behind it a thread of positive space charges. As the first avalanche moves out, this thread is responsible for an increased field between the cathode and the starting point of the thread. Accordingly some electrons, out of the few that have been generated from the outside in the meantime, move toward this head of the space charge thread from the cathode. Because the field is now higher they ionize closer to the cathode than the first electron, so that there are space charge threads branching out toward the cathode from the head of the first one. This process is repeated a few times until the heads of the last space charge threads are close enough to the cathode to generate there fields of sufficient strength to cause cold cathode discharge and breakdown. A close examination of the direction of these branches, conducted by Hippel and by the Russian physicists, Inge and Walter,[17] have shown that these directions have definite orientations in respect to the directions of the crystal. In rock salt in not-too-high fields they are directed along the diagonals of the faces of the cube in which the salt crystallizes. As Hippel has pointed out, that is the direction in which only ions of the same sign are encountered, so that the electric potential due to the charge of the ions building up the lattice is more uniform (less bumpy), and accordingly the chances are greater for the electrons to pass through. It happens repeatedly that in this manner several branches of discharges tear a regular pyramid out of the crystal.

With increasing strength of external fields the electron may travel also along the octahedral edges, where the lattice field is less uniform. The nonuniformity does not matter so much if the external field is strong. In making the experiments it is important, as mentioned previously, that the edge effect (the occurrence of single discharges from the edge of the electrodes) be avoided, as these have an increased field at the end of the positive space charge thread that might induce a breakdown of the crystal before a sufficient strength of field is reached in general.

The dielectric strength of the crystal, avoiding the edge effect, has been investigated by Hippel, Inge and Walter, and Kurtschakoff. In general all these investigators reach the same conclusion: that this strength is of the order of magnitude of one million volts per centimeter, although, according to Hippel,

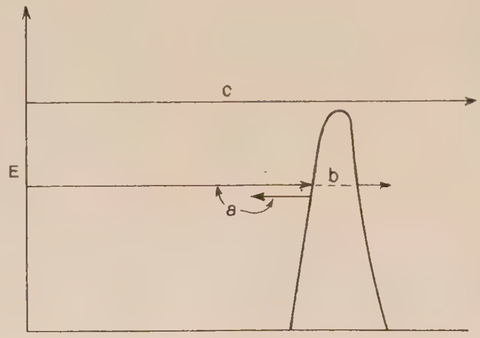


Fig. 1. Behavior of a particle as it strikes a potential barrier

a. Classical-reflection
b. Quantum-tunneling
c. Classical and quantum

it varies systematically with the crystal investigated. He finds for sodium fluoride (NaF) 2.4 million volts per centimeter, for sodium chloride (NaCl) 1.5–0.1, for rubidium iodide (RbI) 0.5, and for magnesium oxide (MgO) the highest strength of all the materials investigated. A calculation of the breakdown potential difference for a distance equal to the distance between 2 ions in the lattice shows it to be of the order of $^1/_{10}$ volt. In comparing this energy with the minimum energy necessary to excite the main vibration of the crystal, Hippel found that for all the crystals investigated the breakdown potential difference over the atomic distance is about 3 times the quantum of the ionic vibration, and interprets this result in the following manner: If the free electrons have just the energy equal to the quantum of the lattice vibration they are more apt to lose it by collision through a kind of resonance phenomenon and therefore cannot accumulate energy sufficient for ionization. If, however, between 2 collisions with ions of the lattice they can gain an energy sufficiently higher than the quantum, the probability of a loss is much smaller and they can proceed to accumulate further energy sufficient for ionization.

New Quantum Theory

There are 2 features in the new quantum theory that are of importance here. In classical theory, if a particle (electron, atom) encounters a potential hump (a place of high positive potential energy) it can pass the hump only if its total energy is greater than the highest value of the potential energy, because the total energy remains constant and the kinetic energy must be positive:

$$\text{Kinetic Energy} = \text{Total Energy} - \text{Potential Energy}$$

In the new theory that no longer is valid. Here electrons behave in many respects like waves, as shown by the beautiful interference experiments of

Davison and Germer. Waves, however, are not stopped immediately by any reflecting material, but can penetrate a thin layer of it and emerge with decreased intensity. Now, a potential wall acts for electrons just as a reflecting surface acts for light waves. Accordingly, electrons can penetrate a thin (Fig. 1) potential ridge, even if their energy is too small to get over the top. However, that is possible only if the ridge is narrow; the probability for penetration or the time it takes on the average to reach the other side of the ridge increases exponentially with the thickness.

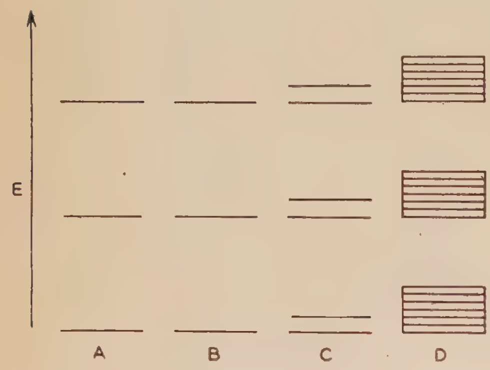


Fig. 2. Illustrating the origin of broad bands in crystals according to quantum theory

A, B. Two free atoms
C. Two atoms close together
D. Crystal

The importance of this phenomenon here is twofold: Firstly, it explains "cold electron discharges," which will be discussed in a subsequent section. Secondly, it emphasizes the fact mentioned before, that even the "free" electrons in metals are subject to forces exerted by the ions of the lattice. In classical theory, an electron could move under the action of an external electrical field if its kinetic energy, which was supposed proportional to the temperature, was sufficient to get it over the potential ridge, otherwise it was to be considered bound. If the ridge was too high (higher than $^3/_2kT$ or about $^1/_{25}$ volt) the electron was considered as bound and, if only such electrons were present, the material was regarded as an insulator. With the new theory, there is no such sharp limit of permitted potential energy, strongly dependent on T, since the electron also can pass through a potential barrier, although the probability of such passage decreases enormously with increases in the height and width of the barrier.

To get now a clearer understanding of the distinction between metal and insulator, it is necessary to turn to the second important new conception, the Pauli exclusion principle:

It is well known that the quantum theory permits only a discreet number of states (orbits with given energies). Assume a number N of separate atoms, say, of silver. Then, for example, each atom will have 3 lowest possible states (the "valence electron" can have 3 states of low energy). (Fig. 2.) All the atoms are alike, of course. If they are allowed to approach more and more, until they form a crystal, they will influence each other; this will lead to the result that instead of having the possibility of N identical lowest states, one for each atom, there are N different but closely adjacent states. A similar effect is obtained if N identical radio-circuits are coupled; the system of circuits then will be found to have N different, although closely adjacent, radio frequencies.[18,19]

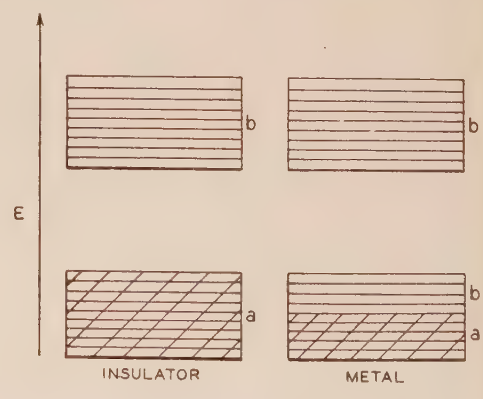
Each state of the free atom gives such a band containing aN states where a_2 is a small integer.

According to Pauli no more than one electron can be in any particular state. If there are N electrons, they will of course fill the states of lowest energy in the lowest band. In case the number of electrons is just equal to the number of states in the lowest band, this band will be completely filled; there will be an equal number of electrons moving to the right and to the left, although how fast they get along will depend upon the height of the potential barriers within the crystal (between the atoms). Of course, because of the equal number going in each direction, there is no resultant current, and this will *not* change upon application of an external field. Such a field could generate a current only if it set more electrons moving, say, to the right. However, that is impossible because all states corresponding to motions to the right already are occupied, and because too much energy is required to put an electron into a higher band that is empty and where the electron therefore could get into a quantum state that corresponds to motion to the right. Therefore, we have an insulator. In a semiconductor, there are impurities that supply electrons into the empty bands of the surrounding medium and give rise to conduction. The same result is accomplished by the action of light of sufficiently short wave length.

If, however, the number of states in the lowest band is larger than the number of electrons present, empty states are available in the same band, and an external electric field has to raise the electrons only to a slightly higher energy to permit an excess of them to travel to one side. We have, therefore, an electronic conductor. There are, however, some electrons in the otherwise empty part of the band that lies above the completely filled part and below the top of the permitted band. The number of these electrons depends strongly upon the temperature.[19,3] See Fig. 3.

Fig. 3. Distinction between a metal and an insulator as explained by quantum theory

a. Full levels
b. Empty levels



Cold Discharge and Detector Action

The theory discussed in the preceding section gives an explanation for the cold electron discharges; that

is, for the possibility of extracting electrons from metals through the action of a high field.

As a result of the attraction of the positive ions, the electrons in the metal are at a negative potential energy with respect to the outer space as zero. The potential difference is of the order of 15 volts, where the electrons of highest kinetic energy at normal temperatures have about 10 volts, so that they have an energy of about 5 volts less than that of the potential barrier. Only at high temperatures are there enough electrons with 15 or more volts kinetic energy to enable them to pass over the barrier (thermoelectronic emission). However, a strong external field can lower the potential energy at some distance from the metal and thus limit the region of high potential to a thin layer at the surface of the metal which layer electrons then can penetrate in spite of the fact that their kinetic energy is not sufficient to carry them over the peak.[20] See Fig. 4.

In a crystal detector[21,22] there is a metal and a semiconductor which is assumed to be separated by a thin, highly insulating layer. When brought into contact, first without external electromotive force applied, electrons will pass from the substance where their energy is higher to the one where it is lower and thus set up a contact potential difference high enough to check this initial flow.

This state is such that the bottom of the first empty band for the electrons in the semiconductor is somewhat higher than the top of the filled portion of the band for the electrons in the metal, and hence the former lies within the height of the empty part of the metal band that is available for conduction. Assume the application of an electric field, as shown in Fig. 5. The potential drop will lie almost entirely in the high resistance of the intermediate layer and we will neglect to a first approximation the field inside metal and semiconductor and the changes it effects in the electron distribution. This change of course will be such as to supply the electrons that will pass out through the insulating layer.

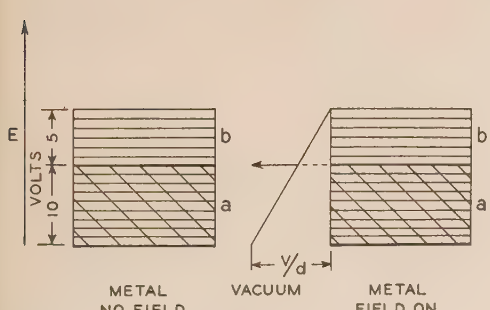
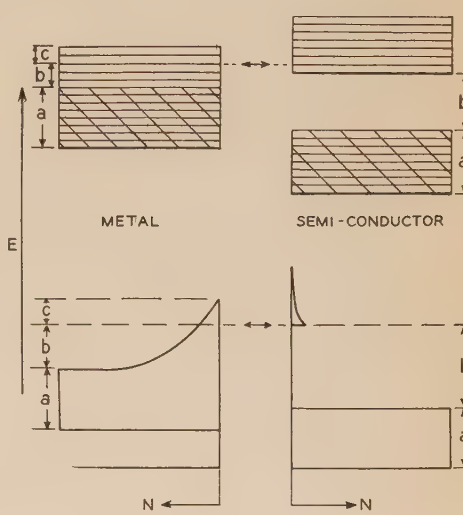


Fig. 4. Diagrams illustrating the possibility of extracting electrons from metals by a strong external field

a. Full levels
b. Empty levels

Assume first that the semiconductor is made negative (direction of high resistance). Without field, there would be an equal number of electrons going from semiconductor to metal and vice versa, therefore no current would be observed. Now, increasing the potential energy of the semiconductor may be said to raise the energy levels of the semiconductor which, although not affecting the number of electrons going from semiconductor to metal, diminishes the number of electrons going in the opposite direction, because fewer now have sufficient energy to reach the lowest empty state in the semiconductor, so that an electron current goes from semiconductor to metal. For high fields a saturation current is reached where no electrons pass from metal to semiconductor. However, if the field is in the opposite direction the potential energy of the electrons in the metal is raised in comparison to those in the semi-

Fig. 5. Metal and semiconductor close together showing electron equilibrium. The electron distribution is shown in the lower diagrams. Raising either metal or semiconductor above the equilibrium causes flow of electrons to the other



conductor, resulting in an increase in the number of electrons passing from the metal to the semiconductor. But, inasmuch as the number of electrons of low kinetic energy is larger than the number with high kinetic energy, the number passing across the boundary increases rapidly (exponentially) with the potential difference, and as a result we have decreasing resistance. At high potential, we obtain rectification and the relation developed on this point of view is given by

$$J = J_0 e^{-\frac{\alpha V\epsilon}{RT}} - e^{(1-\alpha)\frac{V\epsilon}{RT}}$$

where α is a constant between $^1/_2$ and 1. This is the form of equation required by the experiments.

Rectification occurs only if the potential hump in the layer between metal and semiconductor is not too large, that is, if the contact is not too bad.

A different theory has been developed by Schottky and amplified by van Geel.[23] According to this theory the layer between metal and semiconductor is so thick (10^{-4} cm) that no equilibrium is established without external electromotive force. Upon application of an external electromotive force a cold discharge is induced as a result of which electrons leave the negative electrode in an amount determined by the conditions for a cold discharge at this particular electrode, independent of the nature of the other electrode. The rectification is due to the difference in the currents that the same field draws out of the 2 different electrodes. The 2 theories differ experimentally in so far as the first gives a finite constant resistance at very low potential differences, whereas the second gives a resistance which increases to infinity very rapidly for very small fields because

the cold cathode electron discharge is very sensitive to variation in the magnitude of the field.

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The New Italy-Sardinia Cable

A brief description of the deep sea telephone circuit laid in 1932 between Italy and the island of Sardinia is contained in this article.*

Telephone communication between Italy and the island of Sardinia was first established by means of a radio link in September 1930, and the traffic soon became sufficient to justify the laying of a submarine telephone cable. Accordingly, in April 1932, a cable was laid, and in June 1932 it was opened to traffic in connection with the pilgrimages from all parts of the world to Sardinia on the occasion of the fiftieth anniversary of the death of Garibaldi.

The cable consists of a continuously loaded core, with a concentric copper return, similar to the original (1921) Havana-Key West cables. The total length of the submarine part is approximately

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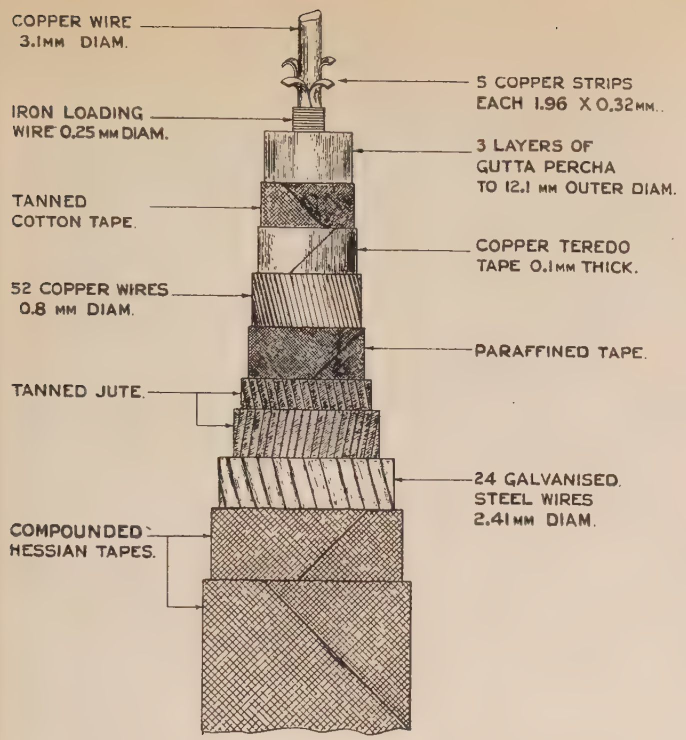

Fig. 1. Construction of the deep sea cable, known as type *D*

146 nautical miles, and it is therefore considerably longer than any submarine telephone cable previously laid. The weights in pounds per nautical mile for the deep sea section are about as follows:

Central conductor	370 lb
Loading	80 lb
Gutta mixture (55 per cent pure gutta)	409 lb
Copper Teredo tape	164 lb
Return conductor	980 lb
Total	2,003 lb

In addition to the telephone circuit, the system was designed to provide 2 duplex telegraph circuits: a low frequency composite channel and a carrier channel. Only the telephone circuit and the low frequency (d-c) composite telegraph channel are equipped at present. The other channel is to be obtained by using carrier frequencies of about 3,000 and 3,500 cycles for the 2 directions.

On the mainland side, the cable is landed at the village of Fiumicino, which is about 18 miles from Rome, and in Sardinia the cable is landed about a mile from Terranova. In each case a cable hut was constructed for terminating the submarine cable and for housing the terminal equipment. Terminal repeater equipment is installed at both ends.

A land cable of special construction was laid be-

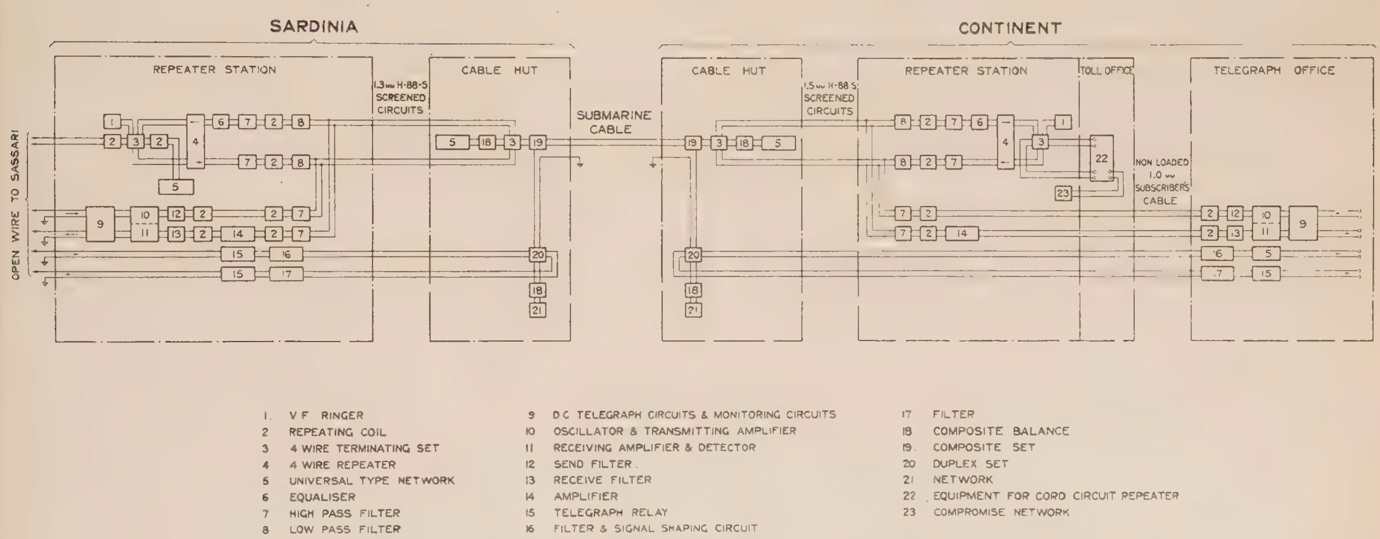

Fig. 2. System schematic diagram of terminal equipment

Table I—Comparison of Submarine Telephone Cables

Cable	Date Laid	Length: Nautical Miles	Length: Kilometers	Max. Depth Fathoms	Core Wts.—Lb per n.m.: Central Conductor	Gutta Percha	Return Conductor
Sicily-Lipari	1920	29	54	400	185	158	(*a*)
Key West-Havana (3 cables)	1921	105	195	1,000	350	315	850
Catalina Island, California (2 cables)	1923	23	43	500	350	App. 500 (*b*)	App. 850
Algeciras-Ceuta	1929	20	37	500	405	450	750
Tenerife-Gran Canaria	1929	40	74	1,500	405	450	750
Key West-Havana	1931	109	202	1,080	505	677 (*c*)	845
Italy-Sardinia	1932	146	270	1,140	370	409	980

(*a*) Figures not available
(*b*) Rubber insulation
(*c*) Paragutta insulation

tween Rome and Fiumicino, and a cable of similar construction was laid between the cable hut and the repeater station in Terranova. Rome and Sassari are the terminals of both the telephone and telegraph circuits, the latter town being connected to the repeater station at Terranova by an open wire line. Connections can be made to other toll circuits by means of cord circuit repeaters. At Rome the cord circuit repeaters are equipped with grid jamming echo suppressors. With this arrangement, when any 2 long distance circuits which are not equipped with echo suppressors are switched together at Rome, the echoes, which would otherwise become

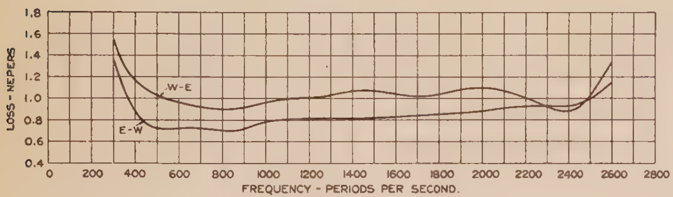

Fig. 3. Over-all loss-frequency curves of repeatered circuit

disturbing on the switched connection, may be suppressed by a comparatively few units of equipment, provided especially for such cases and, therefore, used efficiently.

Owing to the high losses and hence the low receiving levels, many precautions were taken to prevent noise entering the circuit. Screened circuits were used in the tie cables and the equipment wiring of the receiving curcuit was also screened throughout the repeater stations and cable huts.

Direct connection of the land cable pairs to the concentric submarine cable would have led to very considerable difficulties, and in order to avoid them, 4-wire terminating sets and balancing networks were located at the cable huts, 4-wire circuits being provided in the underground cables.

The 4-wire terminating sets thus perform a double function. They form the connecting links between the 2-wire and 4-wire portions of the system at the actual terminals of the submarine cable, thus eliminating the singing point troubles associated with changes of temperature of the land circuits and with differences between the impedances of the underground and submarine cable. They also act as screened repeating coils to connect the low impedance concentric submarine cable with the high impedance metallic land circuits, while, owing to their position in the circuit, changes in the magnetic properties of their cores do not affect the balance between line and network.

The high losses also necessitated paying special attention to the question of allocation; that is, the order in which the coils of core should be joined together in order to obtain as smooth an impedance-frequency curve as possible. This problem was solved by means of a very careful series of measurements on each coil.

A comparison between the Italy-Sardinia cable and cables previously laid is shown in Table I.

Some Recent Relay Developments

Some recent developments in the protection of electric power systems to meet the special problems on the system of the Southern California Edison Company, Ltd., are discussed in this paper. Among these developments are means to provide greater protection against high resistance faults, a simplified carrier current pilot protection scheme, a method of automatic system separation when out-of-step conditions occur, and several miscellaneous applications.

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PROBLEMS of protection requiring unusual relay developments or applications often arise in the course of operation of a large electric power system. Some problems have confronted protection engineers for a long time defying satisfactory solution; among these are the problems of high resistance ground faults, and the problem of adequate protection against 3-phase short circuits which will not be operative during out-of-step conditions on a system. The problem of high-speed single-line protection is gradually approaching solution. This paper presents some of the problems encountered on the system of the Southern California Edison Company, Ltd., and the relay applications used in the solution of those problems.

A sensitive relay has been developed to protect low voltage radial feeders against high resistance ground faults. Protection of high voltage transmission has been reinforced through the use of instantaneous overcurrent relays and application of differential principles of protection in the form of carrier current pilot protection. Another relay has been developed to detect loss of synchronism on the system and to perform switching operations required in such a case. Applications of relays for protecting generators with grounded field windings, generators operated with neutral ungrounded, and generators with neutral grounded through reactors also are described in this paper.

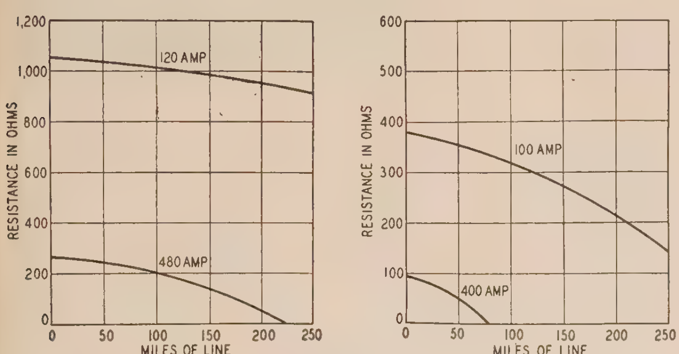
Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted Dec. 18, 1933; released for publication Feb. 7, 1934. *Not published in pamphlet form.*

Ground Fault Resistance

High resistance ground faults represent one of many problems encountered in the operation of high voltage overhead lines. This problem is one of the most difficult to solve on account of the wide variation in fault resistance and its effect at the different voltages and under different fault conditions. The presence of a little resistance in faults to ground on lines of lower voltage may so limit the fault current that the relays will not clear a line that may be a hazard to life and property.

A study of the effect of fault resistance on values of ground current in a single-conductor-to-ground fault on a typical overhead system demonstrates strikingly the importance of ground fault resistance at lower voltages. Figures 1, 2, 3, and 4 present some of the curves plotted from the results of such a study. In these curves the resistance limiting the ground current in a single-conductor-to-ground fault is plotted against the distance along the line from the power supply bus to the fault.

Figures 1 and 2 show typical conditions on the 220-kv and the 66-kv systems. The areas under the



Figs. 1 (left) and 2 (right). Fault resistance limiting residual current to indicated value vs. distance along the line, for a 220-kv line (left) and a 66-kv line (right)

lower curves include faults that can be cleared properly by the existing protective equipment. An average minimum trip value of 480 amp is used on 220-kv lines and 400 amp on 66-kv lines.

From actual records of short circuit currents on the 220-kv system the average fault resistance is in the order of 100 ohms. However, in several cases the fault resistance has been in the order of 300 ohms which is beyond the range of the present single-line protective equipment. With the latest carrier current pilot protection it will be possible to reduce the minimum trip current to $^1/_4$ of its present value and correspondingly increase the range of protection to include the areas under the upper curves of Figs. 1 and 2.

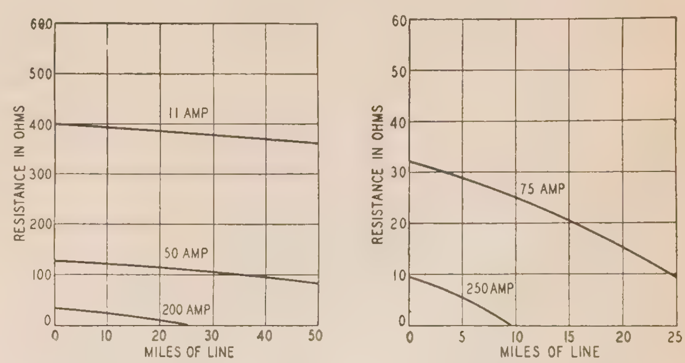
Figure 3 shows conditions on an 11-kv system. For minimum trip values of 200 amp a ground resistance of 25 ohms on a 10-mile section of line will limit the ground current to the minimum trip value; and with residual relays, with 50-amp minimum trip setting, 125 ohms on a 10-mile section of line will produce the same effect. A relay arrangement that will detect residual currents of approximately 10 or 11 amp will clear a fault with 375 to 400 ohms resistance even on a 30-mile section of line.

Figure 4 shows conditions on a 4-kv system. A ground fault resistance of 8 ohms on 2 miles of line will limit the current to the minimum trip value of 250 amp, and 30 ohms will limit the current to 75 amp if residual relays are used. This is still a rather difficult problem to solve on account of the unbalanced load currents due to single-phase connected loads. In order to increase the range of the protective equipment and obtain more sensitive minimum trip settings, the unbalance in load currents must be reduced to a value considerably less than the minimum trip setting.

In connection with the foregoing studies a series of tests were made on an 11-kv line. One end of a length of No. 6 B. & S. gauge copper wire was connected to one of the conductors of the line, and an ammeter was inserted in series with the wire; then the wire was lowered by means of a rope until it made contact with ground, and the ammeter was read through a pair of field glasses. The different readings ranged from 10 to 25 amp depending on whether the wire was lowered on grass, open ground, or dirt road, and on the length of contact with ground. The meaning of the readings will be apparent when the latter are compared with calculated values. Calculated ground current using reactance only was 480 amp, the one obtained when line impedances were used was 290 amp, while the peak load carried by the line was about 50 amp per phase. The fault resistance was of the order of 250 to 460 ohms limiting the current to 25 and 10 amp, respectively.

Distribution Feeder Protection

The relay arrangement proposed for protection of distribution feeders is shown in Fig. 5. It consists of the original phase overcurrent relays and a ground



Figs. 3 (left) and 4 (right). Fault resistance limiting residual current to indicated value vs. distance along the line, for a 11-kv line (left) and a 4-kv line (right)

current directional relay. The directional element of the ground current relay is operated by the current in the return wire of the current transformers; this element selects the faulted line. On a Δ-connected system current for the operating coil is obtained from the series connected secondaries of the

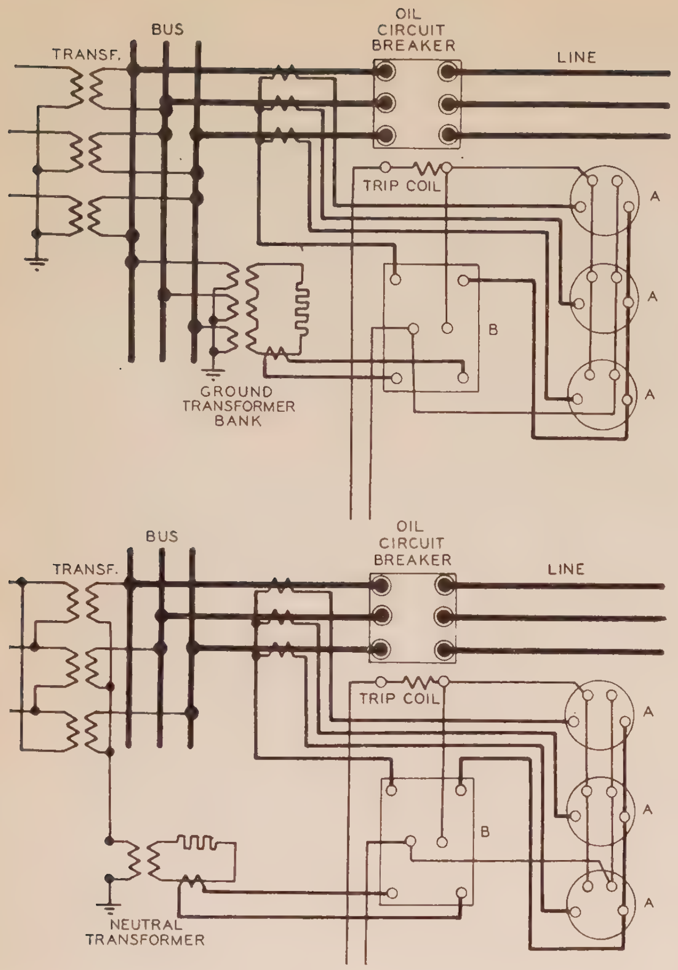


Fig. 5 (left). Wiring diagrams of protection for low voltage distribution feeders. Upper diagram is for a Δ-connected system; lower diagram for a grounded-Y system

A. Phase overcurrent relay

B. Ground current directional relay

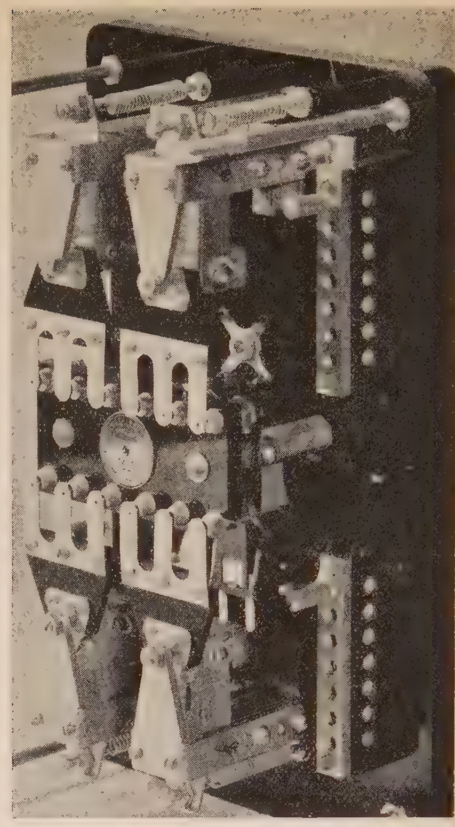


Fig. 6 (right). Instantaneous trip over-current relay

grounding transformer bank; on a grounded-Y system it is obtained through a small transformer connected as shown in the lower diagram of Fig. 5. When several feeders radiate from the bus the operating coils of the ground relays are connected in series. A minimum trip value of 10 amp can be obtained with such a relay arrangement.

High Voltage Line Protection

The general method of protection used on the high voltage transmission lines of the Southern California Edison Company is as follows: Parallel 220-kv lines are equipped with residual current balanced relays. For single line protection residual current directional relays are used where possible and residual overcurrent relays at generating stations and at stations where directional relays cannot be used. Current balance relays protect parallel 66-kv lines, overcurrent relays protect 66-kv lines at 220/66-kv step-down substations, and power directional relays protect 66-kv lines at all secondary substations.

The use of residual currents for protection of 220-kv lines is due to the fact that nearly ninety per cent of the short circuits on these lines are single-conductor-to-ground insulator flashovers. Lower minimum trip settings are possible with residual relays than with relays operated by phase currents. However, a protective system of this kind does not detect 3-phase or phase-to-phase short circuits. An instantaneous overcurrent relay has been designed to supplement the ground current protection; this relay consists of 4 elements of the contactor type mounted in one case (Fig. 6). The coil of each element is provided with taps, and further adjustments are made by varying the air gap and the tension of the opening spring. The closing time of the relay is half a cycle and its performance is very consistent. Three of the elements are operated by phase currents and the fourth one by residual current. When these relays are set properly to be inoperative on out-of-step conditions and on short circuits on other sections of line, they protect an average of about 40 per cent of the line from the station. A line with a short circuit within this distance is relayed first at the nearest station and subsequently at the other end. The additional instantaneous relays fail to protect a short section near the middle of the line, and they operate in sequence which also is an undesirable feature.

Carrier Current Pilot Protection

Latest developments in carrier current telephony provide means for applying differential principles to the protection of long transmission lines, thus eliminating sequential relaying and permitting lower current and time settings. (See "Development of a Relay Protective System on the Lines of the Southern California Edison Company, Ltd.," by E. R. Stauffacher, A.I.E.E. Trans., v. 50, 1931, p. 80–8.) The current differential type of protection so far developed is very complicated, involving considerable auxiliary equipment to transmit by means of carrier current the phase relation of the current at one end of the line to that at the other end of the line. The

complication of the apparatus and its high cost are the chief drawbacks of this type of carrier current pilot protection. A simpler protective system has been developed by the Southern California Edison Company. It detects power flow from both ends into the line, a condition that exists when a fault or short circuit is on the line. When power flows out of one end of the line the sensitive tripping relays are made inoperative by short circuiting their operating coils. Following are the requirements for an ideal protective system:

1. It must clear all types of faults on the protected line.
2. It must not operate during out-of-step conditions on the system.
3. It must not operate during faults external to the protected line.
4. It must not fail to trip when the interlocking circuits are interrupted.
5. It must eliminate sequential relaying.
6. It must be faster than other types of protection.

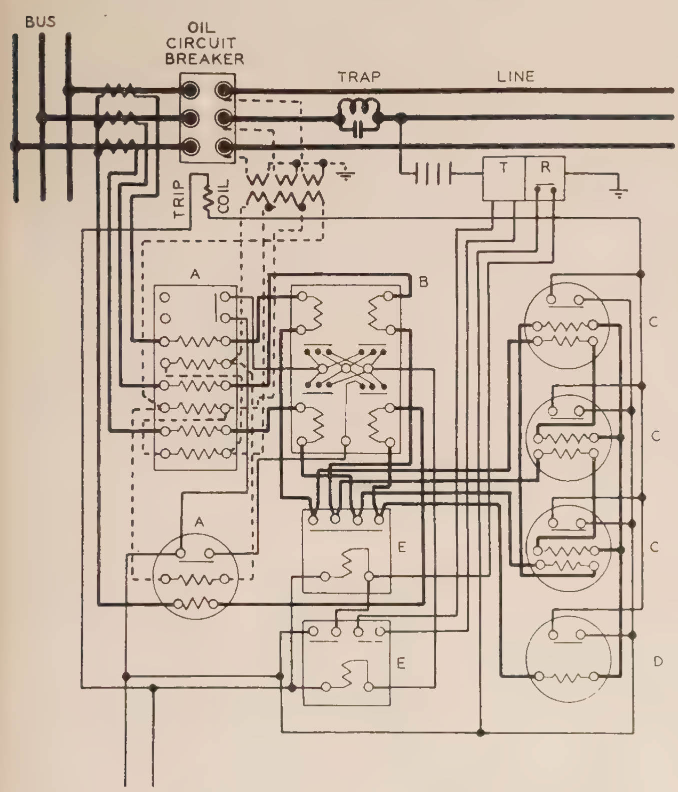


Fig. 7. Wiring diagram of carrier current pilot protection

A. Power directional relays
B. Instantaneous current relays
C. Current balance relays
D. Overcurrent relay
E. Auxiliary relays
T. Carrier transmitter
R. Carrier receiver

Unfortunately, requirements 1 and 2 cannot be met on systems where synchronous machinery is present at both ends of the line since out-of-step conditions correspond to an intermittent 3-phase short circuit at the electrical center of the system. It becomes necessary, therefore, to sacrifice one requirement in favor of the other. When the first requirement is to be met, overcurrent relays are used and a false operation during out-of-step conditions can be expected; when the second is to be met, current balance relays are used and the line is not protected against balanced 3-phase short circuits. The latter is shown in the wiring diagram of Fig. 7. The power directional relays are so connected that their contacts close when the direction of power is from the line to the bus. The contacts of the instantaneous overcurrent relays are in series with those of the directional relays in order to prevent locking out on load currents. When both the directional and the instantaneous relays operate and have their contacts closed, the lower auxiliary relay is energized and its 2 contacts close. One contact energizes the upper auxiliary relay, and the closing of the second contact transmits a signal to the other end of the line where it energizes the upper auxiliary relay. The upper auxiliary relay short-circuits the coils of the current balance or overcurrent tripping relays. The contact resistance of the auxiliary relay must be very low.

Time involved in the operation of this protective system is as shown in the oscillogram reproduced in Fig. 8. Less than a cycle is required for the contacts of the directional and instantaneous relays to close, less than a cycle for the lockout signal to be received at the other end of the line, and less than a cycle for the upper auxiliary relay to short circuit the coils of the tripping relays. A total time of $2^1/_2$ cycles is

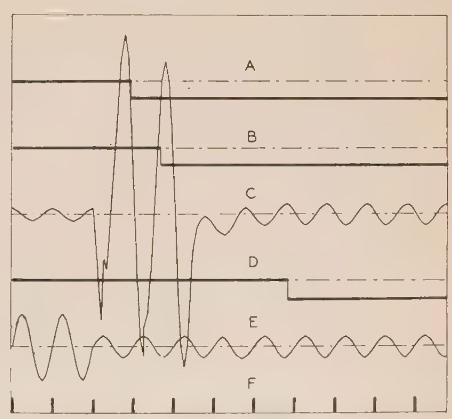


Fig. 8. Reproduction of an oscillogram showing performance of carrier current pilot protection

A. Operation of directional relay (external)
B. Lockout received at far end of line (external)
C. Current in tripping relays (external)
D. Operation of tripping relays (internal)
E. Voltage on directional relay
F. 50-cycle timing wave

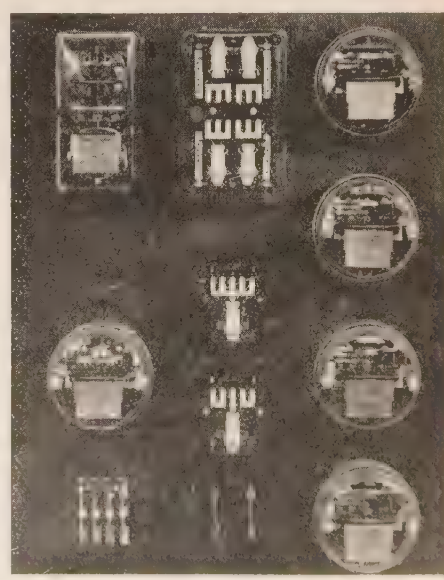


Fig. 9. An experimental carrier current pilot protection relay panel

required for the lockout operation. The operating time of the tripping relays also is shown on the oscillogram, and is seen to be 5 cycles at 2,000 per cent tripping current.

Figure 9 shows 1 of the 2 experimental relay panels that were subjected to severe tests in the laboratory and in the field. The laboratory tests similated all types of faults and short circuits of a wide range of current and voltage values internal and external to the protected apparatus. Every test was repeated with out-of-step conditions on the experimental system. The relay panels then were installed on a 16.5-kv transmission line and tested by applying all types of faults and short circuits to that line and to another line operated from the load end bus. The field tests were successful and many oscillograms were taken to substantiate laboratory tests and to indicate direction for improvements. A permanent installation was made on the East Gould-Laguna Bell 220-kv line, and its performance is being carefully observed.

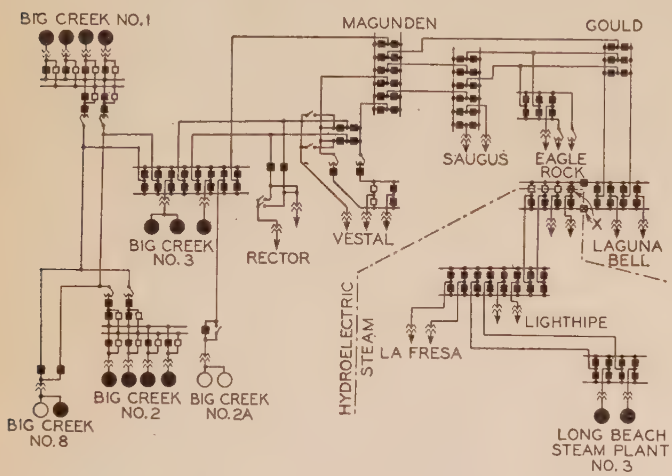


Fig. 10. Schematic diagram of 220-kv transmission system showing point of separation

■—Switches closed □—Switches open
X—Switches opened during out-of-step conditions to effect separation

Automatic System Separation

When out-of-step conditions occur on the system of the Southern California Edison Company, the following procedure is used to restore normal operation: The system is separated into 2 groups, hydroelectric and steam; and after normal speed and voltage are obtained on the 2 separate groups, they are paralleled again at the point of separation. The point of separation is established beforehand, it being determined by generating capacity on line at the Long Beach steam station and loads on transformer banks at the nearest substations. A typical operating arrangement is shown in Fig. 10. In this particular case 200,000 kw of generating capacity is on line at the Long Beach station, and the separation point is shown at Laguna Bell by the 2 oil circuit breakers with crossing diagonals. After separation the steam station would carry La Fresa, Lighthipe, and 2 transformer banks at Laguna Bell, the balance of the system load being left with the hydroelectric plants.

On several occasions it was observed that when out-of-step conditions exist on the system, the synchronous condensers slow down to about 70 per cent of synchronous speed and run at that speed until switched off the line or until operating conditions are altered in some other way. If the system is allowed to operate for any length of time under such conditions, the condenser and generator damper windings and field structures will overheat rapidly and eventually will burn out. (See "Out-of-Step Conditions on a Synchronous System," by Alex A. Kroneberg, Electrical Engineering, v. 51, Nov. 1932, p. 769–72.) The synchronous condensers were equipped with underspeed relays which trip the condenser oil circuit breakers when the speed drops to 88 per cent of synchronous speed.

System separation is performed when the operator observes from his indicating meters that out-of-step conditions exist on the system. A relay has been developed which automatically will detect out-of-step conditions and perform the separation. This relay consists of 3 instantaneous overcurrent elements operated by the total phase currents in both lines feeding the substation from the steam station. The contacts of these 3 elements are connected in series and they operate a ratchet type relay. The ratchet relay operates when energized from 3 to 10 times per second; an auxiliary relay energized by the ratchet relay trips the oil circuit breakers selected for the separation. A simple schematic diagram of the automatic separation relay is shown in Fig. 11.

Faults involving 1 or 2 conductors will operate only that many instantaneous overcurrent elements, and the circuit of the ratchet relay will not be completed. Balanced 3-phase short circuits will bring up all 3 elements only once and will move the ratchet relay one notch. During out-of-step conditions, however, the ratchet relay will be operated more than once. It can be set to operate on 2, 3, or 4 current swings.

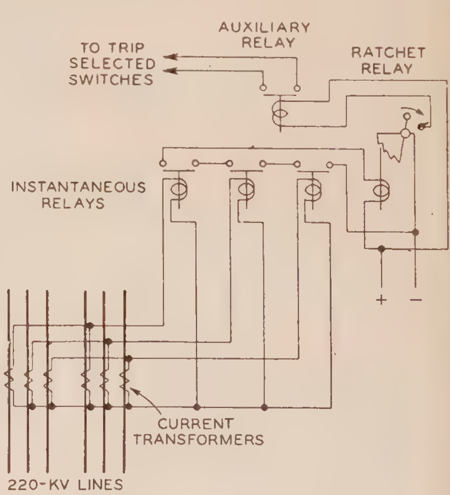


Fig. 11. Schematic diagram of automatic separation relay

Miscellaneous Relay Applications

Internal faults sometimes are detected on generators that cannot be taken out of service for repairs

without affecting operating economies. For example, failures of insulation to ground in the fields of 2 17,500-kw water-wheel generators were detected at Kern River No. 3 powerhouse during the spring run-off. Kern River No. 3 is a river flow plant with no facilities for storage. It was desired to keep the generators in service until fall when the flow of the river is low and the powerhouse operates at a fraction of its capacity. At the same time it was feared that a second fault to ground at some other point in field windings would result in serious damage to the machine. The situation was met by applying additional protection based upon the principle of a Wheatstone bridge. A 500-ohm potentiometer was connected across the field terminals, and a sensitive relay was connected from the sliding contact to ground. The point of zero potential to ground was located on the potentiometer, after which the sliding contact was clamped at that point. The contacts of the relay were connected in parallel with contacts of the armature differential relays. With this scheme of protection in operation, the generators were kept in service until conditions of river flow permitted their removal for repairs.

A somewhat similar problem was encountered at Big Creek No. 1 hydroelectric plant where a 28,000-kw generator relayed on differential protection, indicating a fault to ground in the armature windings. This generator is Y-connected with the neutral solidly grounded, and is tied to Δ-connected low voltage windings of a transformer bank. A high potential test with the machine at standstill failed to detect the location of the fault, making quick repairs problematical; therefore, the unit was placed back in service with its neutral disconnected from ground. In order to detect the recurrence of the ground fault 3 potential transformers were connected to the generator terminals. The primaries of the potential transformers were Y-connected with grounded neutral; the secondaries were connected in series and a bell ringing voltage relay and voltmeter were connected in the circuit.

With generators operating successfully with the foregoing arrangement, it was decided to use ground detectors and lift the neutrals on old synchronous machines on which insulation failure can be expected. Two types of ground detectors were devised, the one best fitting the physical layout of the generator to be used in each case: The first type was as described in the preceding paragraph; the second one was composed of a potential transformer the primary of which was connected from neutral to ground, and the secondary to a voltmeter and a bell ringing relay. The 2 types are shown in Fig. 13.

Additions of equipment to existing installations, particularly additions of current limiting reactors, often affect the sensitivity of existing relay protection. In cases of this kind additional protection must be developed. When current limiting reactors were installed in the neutral-to-ground connections of the 100,000-kw generators at Long Beach No. 3 steam plant, the current that would result from a fault to ground at the terminals of the Δ-connected low voltage sides of their transformer banks would be limited to only 20 per cent of the minimum trip value of the transformer differential relays. In order to protect the low voltage windings of the transformer bank and the leads and equipment between the windings and the region covered by the generator differential protection, an induction type overcurrent relay with a current transformer of sufficiently low ratio was connected in the neutral of each generator. The tripping contact of this relay was made to operate in parallel with the original transformer differential protection.

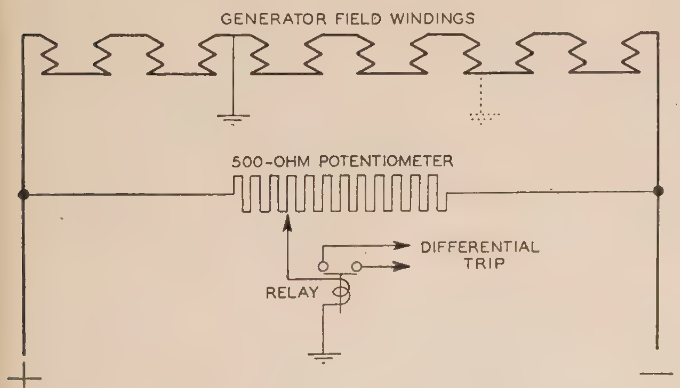
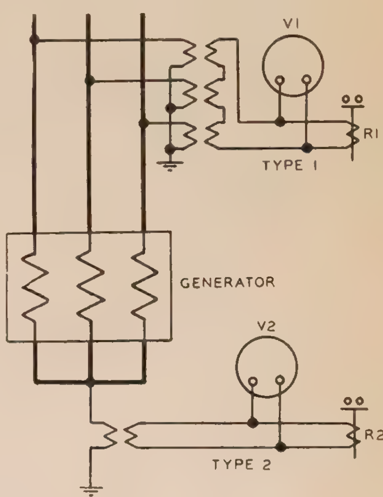


Fig. 12. Wiring diagram of field protection for 2 generators having grounded field windings at Kern River No. 3 powerhouse

Fig. 13. Schematic diagram of ground detectors

V1. 200-volt voltmeter
V2. 67-volt voltmeter
R1. 20-volt bell ringing relay
R2. 7-volt bell ringing relay



Conclusion

In concluding, it can be said that nearly all problems of protection can be solved by exercising ingenuity in the application of standard relays and equipment or in the design of new relays. There is, however, an aspect which must be considered and that is the economic justification of the relay application. The cost of relaying equipment often makes it economically unsound to protect transmission lines properly, thus compelling the abandonment of reliability of service in favor of safety to life and property.

Induction Motor

Locked Saturation Curves

Predetermination of the bend in the locked saturation curves of squirrel cage induction motors is becoming increasingly necessary for design. The reasons why this curve deviates from a straight line are discussed in this paper, and a method of attacking the problem is given. Results calculated by this method for a number of machines are compared with the tested results. It is shown that the work involved in using the formulas and curves presented is not excessive.

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IN THE design of squirrel cage induction motors it is important that some method of calculating the locked saturation curve be available in order to insure the proper values of locked rotor amperes and of starting torque. This saturation curve, expressed in locked rotor amperes for different applied voltages, tends to curve upward, and it is the deviation from a straight line which is considered in this paper. It is shown that, under certain conditions, an economy may be effected by the method presented herein.

Reason for This Work

Induction motors have always been popular because of their simplicity and consequent lack of trouble in operation; but the heavy current that the normal induction motor draws from the line at the instant of start has been a characteristic which has received its share of criticism. This criticism was met some years ago by offering 2 other types of squirrel cage induction motors in addition to the standard motors. They were the "line-start" motor having low starting current and normal starting torque, and the "line-start" motor having low starting current and high starting torque.

The problem for the designer of these motors is to obtain the required starting torque with the reduced starting current and at the same time keep the rotor running resistance sufficiently low to prevent the speed at full load from falling too far below synchronous speed.

If the starting current of any induction motor were exactly proportional to the applied voltage, then, assuming that the reactance formulas used were reliable, a given rating could be designed so that the starting current would come close to the limit set; and the starting torque would consequently test close to the calculated value. However, it is seldom that the starting current is exactly proportional to the voltage and if plotted against voltage it will usually be found to increase faster than the voltage is increased.

Now suppose that the reactance formulas give results which check the lower part of this curve, then the calculated starting current at full voltage will be lower than the test with the possibility that the test will exceed the guaranteed limit.

Suppose that to meet this eventuality the current is assumed to increase a certain percentage and the guaranteed starting torque will just be met if the current does make this increase; then, should the locked saturation curve be straighter than antici-

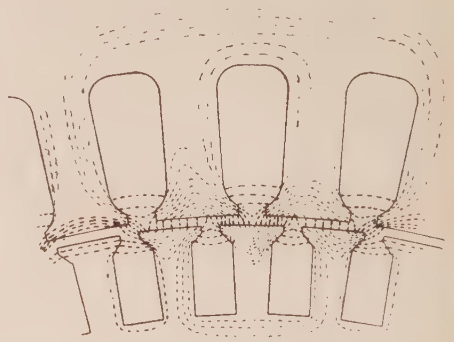

Fig. 1. Illustration of zigzag and tooth-tip leakage flux

pated, the starting torque will fall short of the guaranteed amount.

To endeavor to meet the current limit if the curve bends up, and at the same time the torque limit if the curve is straight, is in most cases impossible, as the current is usually well up to the limit when the motor delivers the required torque. As the tendency has been to reduce the number of primary slots to the minimum in order to lower the cost of production, this situation has become more pronounced because the locked saturation curve tests straighter for the design which has the greater number of slots.

Of course, if there has already been a test taken on a motor which is similar to the contemplated design then it is possible to interpret the locked saturation curve of this old design so as to be sure of the performance of the new design; but if there is no such test available, then the previous arguments show why some method of calculation for this possible increase in current could be used to advantage.

Nature of Decrease in Leakage

The cause for the upward bend in the locked saturation curve is well known, this upward bend being due to the saturation of the leakage flux paths

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Jan. 11, 1933; released for publication Aug. 28, 1933. *Not published in pamphlet form.*

with a consequent reduction in counter electromotive force.

Suppose that a motor be started on greatly reduced voltage so that there is no saturation of the leakage flux paths, and that it draws a current of 10 amp from the line. This 10 amp will cause a leakage flux that in turn causes a counter voltage which, when added vectorially to the resistance drop, balances the applied voltage.

Now suppose that the voltage be increased so that the current becomes 50 amp, and that the leakage paths are now saturated; then the leakage flux will not be 5 times as great as in the first case because of the saturation. The counter voltage of the leakage will therefore be less than 5 times what it previously was and when it is added vectorially to the resistance drop, which is 5 times greater than before, it gives a total voltage of less than 5 times the original voltage. Since the current has increased from 10 amp to 50 amp with less than 5 times as much voltage it follows that the curve of amperes against voltage will bend. To be able to predict the amount of bend it is necessary, then, to be able to foretell the decrease in the leakage due to this saturation. The following arguments show how this can be done.

The flux densities of the leakage flux under locked condition are usually high in the iron which is close to the air gap, but low enough at all other points to assume that there is no saturation in the rest of the iron circuit. (See Fig. 1.) It is the zigzag leakage and the tooth-tip leakage that become saturated; and since both of these employ the tooth-tip iron to carry their fluxes, then it follows that they must both be saturated if there should be any saturation. This is an important point for it draws attention to the fact that, to be fundamentally correct, any method of calculating the changes in leakage should require an adjustment on both the zigzag and tooth-tip leakages if any adjustment is necessary.

Derivation of Formulas for Zigzag Leakage Change

Since the zigzag leakage is caused by both the primary and secondary windings then the average of the effect of each must be taken. For a full pitch winding the maximum ampere turns for one primary slot equals the amperes per conductor, times the square root of 2, times the conductors per slot. Each primary slot in which this group is represented has this same magnetomotive force. For a chorded winding, however, some of the slots will have a reduced magnetomotive force and the average is thereby lowered. This is taken care of by multiplying by the term K_s given in Fig. 3.

The peak value of the secondary current per slot with the rotor locked equals the amperes per primary conductor, times the square root of 2, times the primary conductors per slot, times the product of the primary distribution and chord factors, multiplied by the number of primary slots divided by the number of secondary slots. The average value of current per bar over a length corresponding to a primary group is the above peak value multiplied by the primary distribution factor.

The average magnetomotive force per slot is taken as the mean of the 2 average values based upon the above.

However, for some ratings, where the horsepower per pole is small, there may be an appreciable difference at start between the secondary current in terms of the primary and the primary current itself. To compensate for this the average magnetomotive force per slot is multiplied by the square root of (the no-load counter voltage divided by the impressed voltage).

This is all expressed in eq 1.

$$(AT) = \text{amperes per conductor} \times \sqrt{2} \times \text{conductors per slot} \times \left\{\frac{K_s + K_c \times K_d^2 \times S_1/S_2}{2}\right\} \times \sqrt{\frac{E_0}{E}}$$

$$= \text{amperes per conductor} \times \text{conductors per slot} \times 0.707 \times \left\{K_s + K_c \times K_d^2 \times \frac{S_1}{S_2}\right\} \sqrt{\frac{E_0}{E}} \qquad (1)$$

Where

(AT) = average magnetomotive force per slot of the primary and secondary over a phase group
K_s = winding constant from Fig. 3
K_c = chord factor
K_d = distribution factor
S_1 = number of primary slots
S_2 = number of secondary slots
E_0 = no-load counter voltage per phase
E = impressed voltage per phase

$\sqrt{\frac{E_0}{E}}$ is usually close to unity and can in most cases be omitted

These average ampere turns drive the zigzag flux across 2 air gaps and through the iron. The problem resolves itself into finding the proportion of the

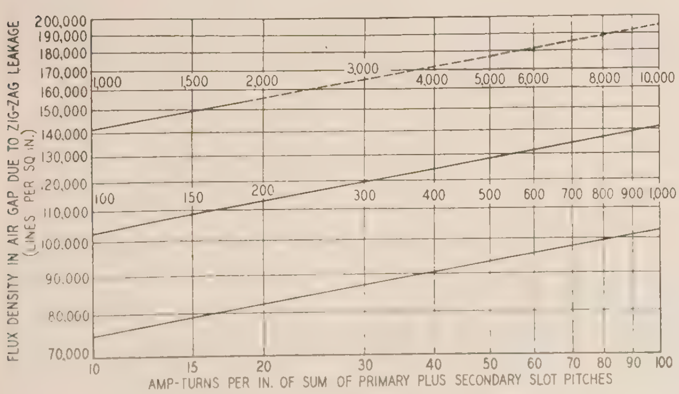

Fig. 2 (left). Iron saturation curve used for zigzag leakage flux

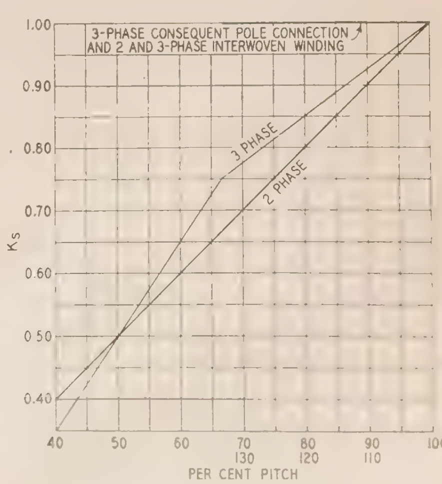

Fig. 3 (right). Curve for finding K_s for different throw or coils

ampere turns required to drive the flux across the air gap twice, to the total ampere turns; for this is the same ratio as the zigzag reactance with saturation to that without saturation.

The following assumptions were made: The saturation curve of the iron for the extremely high densities usually encountered was assumed to be a straight line when plotted on logarithmic section paper; the density in the iron was taken as that in the air gap, and the length of path was assumed to be equal to the sum of the primary and secondary slot pitches. These assumptions were perfectly logical because the position of the straight line can be changed around to compensate for the assumption of the length of path, and also of the density which was taken; and it is true that the saturation curve for high densities in iron does straighten out on logarithmic paper. By working back from tests on various designs the position of the line was found and is shown in Fig. 2.

Taking a particular case where the sum of the slot pitches is assumed to be unity and the air gap 0.02 in., and assuming various densities for the zigzag leakage flux, the ampere turns for the one inch of iron is found by Fig. 2, and that for the air by the usual air gap formula, remembering that there are 2 air gaps involved. Table I shows these figures. The sum of the ampere turns for the iron and the air is tabulated. The ratio of the ampere turns for the gaps to the total ampere turns times 100 gives the per cent zigzag.

If the actual density is divided by the per cent zigzag and multiplied by 100, then a fictitious value of density is found. This fictitious value, however, is the value which is the easier to find from the design of the motor, for it can be found by equating the average ampere turns given in eq 1 to twice the mechanical air gap in the usual formula for flux in air.

The percentage zigzag is plotted against this fictitious density in Fig. 4 together with 4 other similar curves for other ratios of the air gap to the sum of the slot pitches. The curves shown in Fig. 4 cover all the possibilities of this ratio which is encountered in practice.

By examining this family of curves it is found that the center curve alone can be used, which is shown in Fig. 5, provided that an adjustment is made on the value of the fictitious density previously referred to. This adjustment is the value given in eq 3 and it is applied according to eq 4. The curve in Fig. 5 has values according to the last 2 columns of Table I.

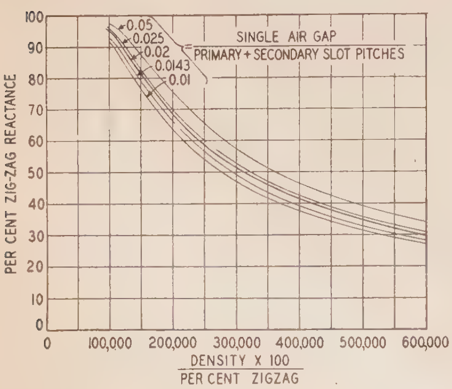

Fig. 4. Curves of per cent zigzag for various ratios of air gap to the sum of the slot pitches

Let

$$\alpha = \frac{\text{single mechanical air gap}}{\text{primary} + \text{secondary slot pitches}} \qquad (2)$$

and

$$\beta = 2.5\sqrt{\alpha} + 0.64 \qquad (3)$$

$$\text{Fictitious } B_L = \frac{(AT)}{0.628 \times g \times \beta} \qquad (4)$$

Where

α and β = constants defined by eqs 2 and 3
Fictitious B_L = fictitious value of air gap density used to find per cent zigzag from Fig. 5
(AT) = ampere turns given by eq 1
g = single mechanical air gap

The per cent zigzag leakage can now be found for any value of line current, air gap, slot pitches, winding, or slot combination by using eqs 1, 2, 3, and 4 and the curves shown in Figs. 3 and 5.

Derivation of Formulas for Tooth-Tip Leakage Change

The tooth-tip leakage is reduced when the zigzag leakage is sufficiently heavy to cause saturation of the tooth tips. The effect is as though the tooth tips were partially removed, or in other words as though the slot openings were enlarged; thereby reducing the leakage flux. By working with a large number of tested motors, so that the assumption could be checked, and manufacturing variations and variations in materials eliminated, the amount that the tooth tips apparently changed was found. This indicated that the tooth face was approximately reduced in the same proportion as the reduction in zigzag leakage.

Using this larger slot opening, the slot leakage

Table I—Figures for 0.02-In. Air Gap and Sum of Slot Pitches Equal to Unity

Zigzag Leakage Air Gap Density. Lines/Sq In.	Amp-Turns for 1 in. of Iron	Amp-Turns for 2 0.02-in. Air Gaps	Total Amp-Turns	% Zigzag	(Zigzag Density × 100) ÷ (% Zigzag)
75,000	10	942	952	99.0	76,000
90,000	39	1,130	1,169	96.8	93,000
95,000	57	1,190	1,247	95.5	99,500
100,000	84	1,254	1,338	93.8	106,600
110,000	165	1,380	1,545	89.3	123,000
120,000	310	1,506	1,816	82.9	145,000
130,000	555	1,630	2,185	74.6	174,300
140,000	940	1,756	2,696	65.2	215,000
150,000	1,560	1,881	3,441	54.7	275,000
160,000	2,400	2,008	4,408	45.6	351,000
170,000	3,750	2,132	5,882	36.3	468,000
180,000	5,650	2,260	7,910	28.5	630,000

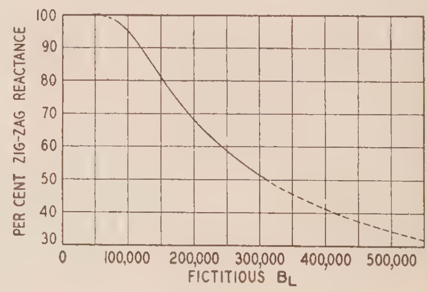

Fig. 5. Curve used to find per cent of zigzag leakage reactance

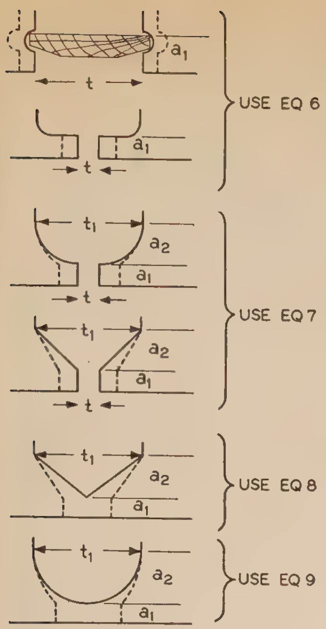

Fig. 6. Various slot shapes and indication of which equation to use

constants are then recalculated and the new slot leakage found from these smaller constants. The calculating of this change in leakage can, however, be reduced by using the formulas of eqs 5 to 9, in conjunction with Fig. 6. In Fig. 6 the sketches of the different slots have dotted lines showing how the slot shape is assumed to change when saturated; the formulas indicated alongside of the different slot shapes give the change in the slot leakage constants. These apply equally well to either the primary or the secondary. The formulas are as follows:

$$C = (\lambda - t)\left\{1 - \frac{\text{Per cent zigzag}}{100}\right\} \tag{5}$$

(See diagrams of Fig. 6 to determine which of the following formulas should be used.)

$$\delta k = \frac{a_1}{t}\left\{\frac{C}{C+t}\right\} \tag{6}$$

$$\delta k = \frac{a_1 + 0.58a_2}{t}\left\{\frac{C}{C+1.5t}\right\} \tag{7}$$

$$\delta k = \frac{a_1}{0.02}\left\{\frac{C}{C+0.02}\right\} + \frac{3.3a_2}{t_1}\left\{\frac{C}{C+0.4t_1}\right\} \tag{8}$$

$$\delta k = \frac{a_1}{0.02}\left\{\frac{C}{C+0.02}\right\} + \frac{2a_2}{t_1}\left\{\frac{C-0.15t_1}{C+0.6t_1}\right\} \tag{9}$$

where

C = apparent change in slot opening due to saturation
λ = slot pitch at air gap (primary or secondary)
δk = change in slot constant (primary or secondary)

For a_1, a_2, t, t_1, see diagrams of Fig. 6.

The derivation of eqs 5 and 6 is as follows:

$\lambda - t$ = unsaturated tooth face

$$(\lambda - t)\frac{\text{Per cent zigzag}}{100} = \text{saturated tooth face}$$

$$C = \lambda - t - (\lambda - t)\frac{\text{Per cent zigzag}}{100}$$

$$= (\lambda - t)\left\{1 - \frac{\text{Per cent zigzag}}{100}\right\}$$

$$\text{Slot constant for tooth tip (unsaturated)} = \frac{a_1}{t}$$

$$\text{Slot constant for tooth tip (saturated)} = \frac{a_1}{C+t}$$

$$\delta k = \frac{a_1}{t} - \frac{a_1}{c+t}$$

$$= \frac{a_1 \times C + a_1 \times t - a_1 \times t}{t(C+t)} = \frac{a_1}{t}\left\{\frac{C}{C+t}\right\}$$

The derivation of eqs 7 to 9 is not given but these equations are derived in a similar manner to eq 6 with the exception that approximations are made to simplify them. These approximations have all been checked for various per cent zigzag leakages and for all likely slot dimensions, and are sufficiently accurate to use.

After the change in the slot constant is found, from whichever of eqs 6 to 9 that applies, the per cent slot leakage is given by inserting this value in eq 10. This is done for both the primary and the secondary.

$$\text{Per cent slot leakage} = 100 \times \frac{\text{normal slot constant} - \delta k}{\text{normal slot constant}} \tag{10}$$

Where

δk = change in the slot leakage constant

The percentage zigzag and both the percentage primary and secondary slot leakage having now been found it only remains to multiply the normally calculated values by these percentages divided by 100 to get the adjusted values. These added to the primary and secondary end leakages which do not change give the total reactance. Adding this vectorially to the resistance gives the new impedance and this combined with the locked amperes assumed when filling out eq 1 gives the voltage necessary to produce this current.

Should this voltage be appreciably different from the full voltage rating of the machine then the full voltage value can be found by plotting the approximately full voltage point together with a reduced voltage point where the current gives a fictitious B_L of 75,000. For this latter point it can be assumed that there is no saturation.

A curve is now drawn through these 2 points and the value of locked amperes for full voltage is taken from this curve. It should be remembered when drawing in this curve that the curvature is greatest at the value of current or voltage that gives a fictitious B_L of approximately 95,000. Therefore the curve will probably be much straighter at full voltage than at this lower voltage. This is evidenced by the curves shown in Figs. 7 and 8. Should it be inconvenient to plot these points then a fairly accurate approximation can be made by using eq 11.

$$\text{Full voltage locked amperes} = \text{assumed amperes} + K\,(\text{full voltage} - \text{calculated voltage}) \tag{11}$$

Where

$$K = \frac{\frac{\text{fictitious } B_L}{100{,}000} - 1}{\frac{\text{fictitious } B_L}{100{,}000}(Z_s) - Z}$$

Z_s = impedance calculated with saturation
Z = normal impedance without saturation

This formula should be filled in with values for the leg of the winding.

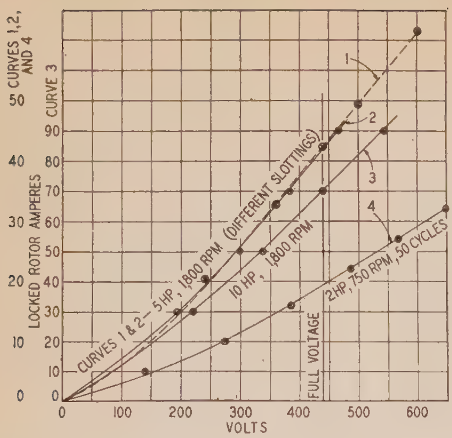

Fig. 7. Locked saturation curves for various ratings having partially closed slot primaries, showing how close the test curves check the calculated points

Curves are test values
Points are calculated values

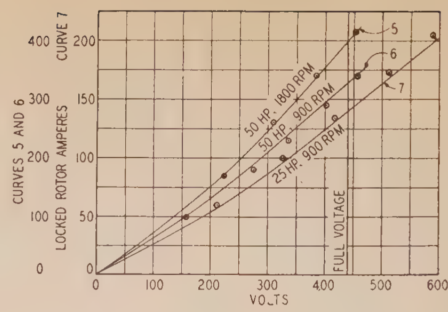

Fig. 8. Locked saturation curves for various ratings having open slot primaries, showing how close the test curves check the calculated points

Curves are test values
Points are calculated values

Comparison of Calculated and Tested Values

If there ever was a mathematical analysis that needed proving it is surely this one. The only justification for publishing these working curves and formulas is that they attain a desired result with reasonable accuracy. It is next to impossible to test the individual steps in the procedure of building up the theory, but it is possible to test the total, and this has been done on many different designs. The calculated values and the test curves of some of these are given in Figs. 7 and 8.

It is seldom that the designer of a new machine is interested in more than the full voltage and some reduced voltage value of locked amperes. However, in checking the previous work a number of points were calculated for various designs for voltages from about 50 per cent to as high as 150 per cent of full voltage, where tests at voltages this high were available. The reason for this is to show that no matter what the field strength should have been for the particular punchings of each machine the calculated locked rotor amperes, using the formulas and curves given in this paper, is very close to the tested result.

The 4 curves shown in Fig. 7 are all for motors having partially closed primary slots. Curves 1, 3, and 4 have bridged secondary slots, while curve 2 is for a secondary having partially closed slots. In Fig. 8 are shown 3 curves for motors having open primary slots and partially closed slot secondaries. It is evident from examination of these curves that the method outlined in this work is well within the accuracy required, especially when it is considered that the difference between tests on 2 motors of the same design will sometimes vary more from each other than the calculated values shown in Figs. 7 and 8 vary from the test values.

One point of special interest is brought out by curves 1 and 2. Curve 1 is for the same rating as curve 2 but the motor has both more primary and secondary slots than the motor for curve 2. The usual calculation for the impedances of these 2 motors is different but the adjusted values of impedance to take into account the saturation of the leakage paths are practically the same for each and the tests indicate that this is correct.

All the curves shown have a decided bend, but there are some designs on which calculations have been carried out, indicating very little change in the reactances; the test shows that this is correct, the locked saturation curve being practically straight.

Curve 1 shows a decided bend for the low voltage values up to about half voltage, which indicates quite a large reactance for these voltages. This is because of the totally bridged rotor slots. Curves 3 and 4 also show this effect, as they are also for motors having bridged rotor slots. No attempt has been made in this paper to try to calculate this particular part of the curve when totally bridged slots are used. However, the effect of added saturation of the bridge due to the presence of zigzag leakage flux is taken into account when the proper formula is used as indicated by Fig. 6.

Scope and Limitations of the Paper

The various formulas are built up with the thought in mind of fitting a wide variety of conditions such as freak slot combinations, multispeed motors, short time ratings where the iron is worked to the limit, ratings having any number of poles, a wide range of air gap possibilities, a range of chording of the winding which covers all that is used in practice, and all the slot shapes usually used at this time including those for double cage and deep bar motors.

The curve given in Fig. 5 has been checked as far down the curve as 50 per cent zigzag against tests on many machines. It is probably correct for much lower percentages, however. Not having sufficient tests at reasonably high voltages to build up other curves similar to that shown in Fig. 5 for high grade silicon irons it cannot be claimed at this time that motors having grades of iron other than the usual low silicon content can be calculated accurately by using Fig. 5.

Since the leakage flux densities vary according to the relative position of the rotor and stator, and also are different for different parts of the tooth end, then it can be seen that Fig. 2 is for the average of all these conditions. Since the saturation curves of low grade and high grade silicon iron cross, then it is probable that Fig. 2, and consequently Fig. 5, are not very far from that which should be used for the different grades of iron encountered.

As explained before, this paper does not take into account the bend in the locked saturation curve which is caused by totally bridged slots, this bend being at much lower voltages than the full voltage. It does, however, enable the upper part of the curve, say from about half voltage, to be calculated.

Another condition that this paper does not cover is that in which the saturation is not primarily caused by the zigzag flux but by the tooth-tip flux, more

often the secondary. In this case, which is most marked for a buried winding machine, the magnetomotive force of the slot is great enough to drive a sufficient flux across from one tooth tip to the other to cause saturation of these tooth tips. This in turn causes saturation of the zigzag leakage flux.

It is possible to calculate the decrease in both leakages by making up suitable curves and reversing the procedure outlined in this work; in other words, the per cent secondary leakage is calculated first and then from this the percentage zigzag is found.

This problem does not lend itself to clean cut formulas, however; and for this reason, together with the fact that the bend is not so great as that which can be caused by the zigzag magnetomotive force when it is the prime cause of the saturation, no attempt has been made here to cover this particular case.

Other than these limitations it is believed that this paper covers all the possibilities met with in practice today, and that in so doing it will help in the more precise design of ratings where the starting requirements are exacting.

In the opening paragraphs it was pointed out that the locked saturation curve bends more as the number of slots is reduced. It is also true that as the iron dimensions are reduced the curve also bends to a greater degree, as the saturation is naturally higher to maintain the torques required for the rating. In the effort to try to design these squirrel cage motors economically the aim has been in the direction of fewer slots, or smaller iron dimensions, or both; but the difficulties encountered by the problematical effect of the saturated leakage paths with no method available to calculate its effect has naturally had the tendency with some designers to limit their steps of economizing in these directions. It is hoped that this paper will help to lift this barrier to progress in the direction of more economical motors.

Appendix—Calculation of a 7.5-Hp 1,800-Rpm Motor

This motor had 36 primary slots and was delta connected. There were 60 conductors per slot and the throw of the coils was 1 to 8. The full rating was 7.5 hp, 1,800 rpm, 3 phase, 60 cycles, 440 volts. The total resistance of the primary and secondary windings with 10 per cent added for eddy current effect and higher temperature encountered under locked condition = 6.3 ohms per leg of the winding.

The reactances calculated without any adjustment for saturation were:

Primary slot	=	3.51
Secondary slot	=	2.42
Primary and secondary end	=	3.68
Zigzag	=	7.19
Total reactance	=	16.8

ohms per leg of the winding. The impedance = $\sqrt{(16.8)^2 + (6.3)^2} = 17.94$ ohms.

If there were no saturation of the leakage paths, then the locked rotor current would equal $\sqrt{3} \times 440/17.94$, or 42.4 amp in the line.

Assume that the current bends up to 53 amp in the line for some voltage near 440, then from eq 1:

$$(AT) = \frac{53}{\sqrt{3}} \times 60 \times 0.707 \left\{0.834 + (0.96)^2 \times 0.94 \times \frac{36}{48}\right\} = 1{,}930$$

because $K_s = 0.834$, $K_d = 0.96$, and $K_\sigma = 0.94$.

The air gap equaled 0.015 in., and the primary slot pitch equaled 0.611 in., and the secondary 0.456 in.

$\alpha = 0.015/(0.611 + 0.456) = 0.01406$, from eq 2

$\beta = 2.5\sqrt{0.01406} + 0.64 = 0.936$, from eq 3

Fictitious $B_L = \dfrac{1{,}930}{0.628 \times 0.015 \times 0.936} = 219{,}000$, from eq 4

Per cent zigzag = 64.3, from Fig. 5

For the primary $t = 0.12$, $a_1 = 0.05$, $a_2 = 0.125$

Primary $C = (0.611 - 0.12)(1 - 0.643) = 0.175$, from eq 5

$$\text{Primary } \delta k = \frac{0.05 + 0.58 \times 0.125}{0.12}\left\{\frac{0.175}{0.175 + 1.5 \times 0.12}\right\} = 0.50 \text{ from eq 7}$$

$$\text{Per cent primary slot leakage} = 100 \times \frac{2.25 - 0.50}{2.25} = 78, \text{ from eq 10}$$

For the secondary the opening = zero, $a_1 = 0.005$, $a_2 = 0.06$, $t_1 = 0.165$

Secondary $C = 0.456\ (1 - 0.643) = 0.163$, from eq 5

$$\text{Secondary } \delta k = \frac{0.005}{0.02}\left\{\frac{0.163}{0.163 + 0.02}\right\} + \frac{3.3 \times 0.06}{0.165}\left\{\frac{0.163}{0.163 + 0.4 \times 0.165}\right\} = 1.08, \text{ from eq 8}$$

$$\text{Per cent secondary slot leakage} = 100 \times \frac{2.17 - 1.08}{2.17} = 50, \text{ from eq 10}$$

The reactances with 53 amp flowing in the line equal:

Primary slot	= 3.51 × 0.78	= 2.74
Secondary slot	= 2.42 × 0.50	= 1.21
Ends	=	3.68
Zigzag	= 7.19 × 0.643	= 4.62
Total reactance		= 12.25

$Z = \sqrt{(12.25)^2 + (6.3)^2} = 13.78$

$$\text{Voltage} = \frac{53 \times 13.78}{\sqrt{3}} = 422$$

In Fig. 9 is shown the point 53 amp and 422 volts plotted together with the point 18 amp and 186.7 volts, the 18 amp being the value of current which gives a fictitious B_L of 75,000, approximately. At this point the curve begins to bend, and it has its greatest curvature approximately at the 23-amp point. As explained before, it straightens out again as the current and voltage increase. Knowing these characteristics, the curve can be drawn in accurately enough to get the full voltage point, which shows 56.1 amp for 440 volts. The test curve shows 57.4 for 440 volts which is about 2.4 per cent higher. Had the saturation of the leakage paths not been taken into account, then the calculated value would have been taken as 42.4, the test value of 57.4 being 35.4 per cent higher.

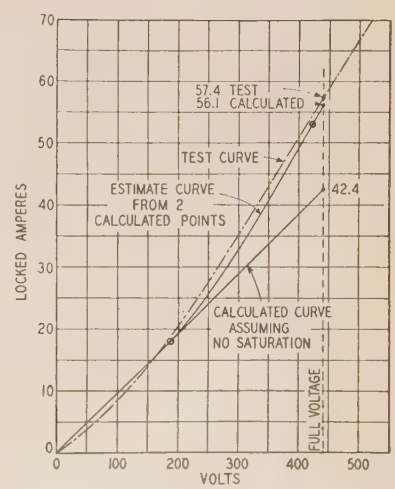

Fig. 9. Illustrates method used to find full voltage locked rotor amperes

It is interesting here to note that the value obtained from eq 11 which eliminates the necessity of plotting the points and drawing in a curve, is 56 for the current in the line as compared to 56.1 found from the curve.

Recent Developments in Power Line Carrier

Some recent developments in power line carrier telephone equipment that greatly enhance the value of this type of communication are described in this paper. Two outstanding developments have been an automatic volume control, and means for interconnecting the carrier circuits with 2-wire telephone facilities. In addition, much has been achieved in lowering installation and maintenance costs, and in improving reliability of operation.

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IN THE OPERATION of power transmission systems, carrier telephony over power conductors has been of great service over the longer distances and where it is necessary to reach power plants in sparsely settled locations. It also has been viewed to some extent as a communication factor of safety in territories where other communication is normally available.

Many of the early applications were of a character that required the solution only of fundamental problems. Much of the earlier apparatus included no provision for meeting various requirements that have arisen as installations have expanded and power companies have indicated the necessity for greater flexibility in this type of communication.

During the past 10 years the various manufacturers have placed in operation in the United States some 300 station installations. Operating experience with this equipment has been invaluable not only in solving fundamental problems, but also in formulating the more detailed requirements of the power companies. Study of this operating experience and these requirements has led to the development of carrier equipment of a new design embodying features that should render this method of communication of even greater practical value.

It is believed that these developments mark an important advance in power line carrier telephony, in that the more serious technical and economical limitations previously encountered now are removed.

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted Jan. 22, 1934; released for publication March 5, 1934. *Not published in pamphlet form.*

The unit type of mechanical design permits manufacture of standard unit assemblies that can be used in many special and unusual combinations, in addition to the 8 standard simplex and 6 duplex assemblies. Much has been achieved in lowering installation and maintenance costs, and in improving reliability of operation. Interchangeability of units provides a means of easily adapting the carrier system as a whole to changes in communication requirements as they arise, even to the extent of converting "simplex" into "duplex" assemblies.

Electrically, the new circuits eliminate serious variations in received signal levels, and afford trunk line service through standard means of connecting the carrier to existing private branch exchange boards and other telephone terminal facilities. The usefulness of power line carrier telephony is much enhanced and the field of application considerably enlarged.

Advantages of Single-Frequency Systems

For a large part of this communication field the use of a single carrier frequency per communication channel has been conceded quite generally to have a number of inherent advantages over methods employing 2 frequencies per channel. Conservation of available frequencies and channels, minimum effect of transmission irregularities and switching operations, and equal transmission losses in both directions are outstanding among these advantages. Single-frequency systems reduce appreciably the problems of tuning coupling circuits and permit the full party line communication feature deemed important by many power system operators.

Fig. 1. Single-frequency power line carrier telephone equipment showing 10-watt duplex assembly

With a single-frequency system it is obviously necessary that the transmitter operate only during speech or call transmission, and that during periods of transmitted speech the associated receiver be effectively blocked. The simplest and least costly method of accomplishing this is by manual control, a button conveniently located on the handset being depressed while talking and released while listening. This method of operation generally is referred to as "simplex." Methods of automatic control by means of voice-actuated schemes generally are referred to as "duplex." Thus in connection with power line carrier telephony the terms "simplex" and "duplex" have meanings slightly different from those with which they are associated in wire line telephone and telegraph practice.

Simplex carrier apparatus has found rather wide application in power dispatching communication and for patrol and unattended stations. In the development and design of simplex apparatus the problems have been quite fundamental in nature.

Duplex apparatus, however, has required much more extensive study and development. Here there has been a growing demand for more flexibility so that a communication problem might be met more economically by applying only those elements of apparatus required for the particular case, but with the possibility of making additions or alterations, conveniently and at reasonable cost, as requirements changed. In this connection there has been a demand for duplex apparatus that might initially be installed for simplex operation.

Two outstanding and related problems have been the development of an automatic volume control and a means of readily interconnecting carrier equipment with 2-wire telephone facilities involved in direct extensions or those through private branch exchange boards. A volume control was required that automatically would compensate for variations in signal levels due to the different power line distances between stations and due to varying conditions on the power transmission lines such as switching. The volume control constituted the prior problem in that a substantially constant audio output level from the receiver was essential to the development of the 2-wire extension apparatus.

In considering this extension apparatus there was sought the complete elimination of the hybrid transformer and wire-line balance network which has proved successful only under rather limited conditions. Effort also has been made to increase reliability and reduce maintenance by the elimination of all batteries and multiple-unit motor generators supplying the various demands for potential. Much attention also has been given to minimizing wear on relays and selector mechanisms. Another point worthy of mention is that considerable provision has been made to accommodate in the standard equipment any apparatus required for special problems.

Several years pursuit of these various objectives have culminated in the design illustrated in Fig. 1. The equipment is divided into main units, each assembled on a separate shelf, mounted in an enclosing steel cabinet. Some shelves embrace several subunits. These units and subunits are used in various combinations to form complete equipment of either simplex or duplex type.

Most of the units have separate rectifier and filter equipment for supplying the necessary plate and grid bias voltages to the various vacuum tubes used. This allows these units to operate independently of other units in this respect regardless of the combination used; it also simplifies rectifier design and requires less wiring between units.

The units are designed to operate from a single-phase a-c power station lighting circuit of 110 or 120 volts, 50 or 60 cycles. No rotating machines such as high voltage motor generator sets or ringing converters are used. As provision against failure of the lighting circuit supply, arrangement may be made whereby on such failure a small 2-unit motor alternator or dynamotor starts, operating from the station control battery and furnishing the 110-volt 60-cycle supply normally provided by the lighting circuit. No batteries of any kind are used with any of the units or combinations.

Fig. 2. Basic 10-watt transmitter unit

The interior of the cabinet, the shelf supports, and all of the shelf units are finished in aluminum paint. This finish gives the equipment a pleasing clean-cut appearance and is very durable. It also contributes to ease in maintenance by the better reflection of light in the interior of the cabinet. The exterior of the cabinet is finished in a dull black to conform with other interior station apparatus.

Description of Units

With the exception of the relay units, which are divided into sections to accommodate the subunits or attachment units, a uniform type of mechanical construction is used throughout. Details of this construction are shown in Figs. 2, 3, 4, and 6. The base is formed by bending down the front and rear edges of a flat steel sheet to give the equivalent of a shallow channel section 15 in. wide by $32^1/_2$ in. long and $2^1/_2$ in. deep. All of the main apparatus parts such as transformers, reactors, and vacuum tubes, are mounted on top with terminals extending through to the under side where are located small parts such as resistors and small fixed condensers. As shown in Fig. 4, the main terminal blocks and practically all of the wiring also are located on the under side.

Fig. 3. Receiver unit

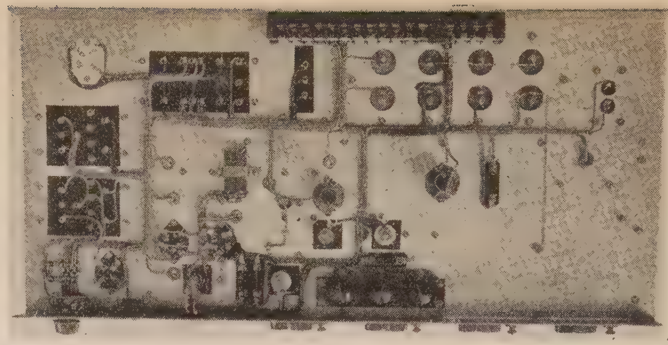

Fig. 4. Receiver unit showing wiring restricted entirely to under side of base

This arrangement simplifies manufacture and permits the terminals of all parts to be reached easily for testing or inspection.

The units are supported by means of angle pieces at the sides of the cabinet and held in place by bolts extending through the shelf and the supporting angles. However, for increased accessibility, the shelves may be pulled forward and tilted up or down.

Transmitter Unit. The unit illustrated in Fig. 2 is used as the basic transmitter portion of all transmitter-receiver assemblies, both simplex and duplex. A modified Hartley type master oscillator, covering a frequency range of from 50 to 150 kc, provides excitation for a class *C* power amplifier to produce a normal carrier output of 10 watts. The modulator circuit uses 2 tubes of the zero grid bias type operating class *B* push-pull, and produces sufficient output on voice frequency peaks to modulate the 10-watt carrier 100 per cent. A class *A* speech amplifier tube prevents speech distortion by supplying the modulator grid losses. All filament and plate voltages for the vacuum tubes of this unit are cut off during "stand-by" periods. The rectifier circuit, which supplies plate and grid bias voltage for these tubes, uses a small full wave rectifier tube of the mercury vapor type. Because of its slower starting characteristics the filament of this tube normally is arranged to operate continuously.

The 3-winding output transformer of this unit is designed to work either into output circuits using cable or open-wire lead-in construction, or into the grid tank circuit of the output amplifier unit when the latter forms a part of the assembly. To provide "intersystem" operation, where the same equipment is used to communicate on either of 2 channels of differing frequencies, provision is made on this unit for the addition of a second master oscillator variable condenser and a relay to accomplish the necessary switching operation.

Output Amplifier Unit. Where communication distances or transmission losses require greater transmitter output than that provided by the transmitter unit, an output amplifier can be used with both simplex and duplex assemblies to obtain an unmodulated carrier output of 50 watts, and a peak power output of 200 watts with complete modulation. Two 50-watt tubes are used in a class *B* push-pull linear amplifier circuit. Excitation for the grids is obtained from a grid tank circuit consisting of a tapped inductance and a variable capacitor which, in turn, is fed from the output transformer of the transmitter unit. Two half-wave rectifier tubes of the mercury vapor type supply the 1,000-volt d-c plate potential. The output transformer of this unit is designed to operate into circuits using either cable or open-wire lead-in construction.

Receiver Unit. Figures 3 and 4 show 2 views of the receiver unit used with all simplex and duplex assemblies. This receiver has a number of unusual features. Referring to the simplified schematic diagram, Fig. 5, the 3 inductively coupled circuits preceding the carrier frequency amplifier tube *V-1* are tuned by means of individual variable condensers, to form a band pass filter adjustable to any frequency in the 50-to-150-kc range. The plate circuit of the screen-grid variable-amplification-factor tube *V-1* also is tuned to the carrier frequency resulting in an over-all characteristic of the filter and amplifier such that side-band frequencies within 3,000 cycles from the carrier are not attenuated appreciably. At the same time, the selectivity obtained permits adjacent channels to be spaced from 10 kc apart at the lower, to 15 kc apart at the upper end of the range.

The detector or demodulator, *V-2*, is a 3-element vacuum tube of the indirectly heated cathode type. The 2 secondary windings of the detector output transformer are connected to the amplifier tube *V-3* and to a 500-ohm telephone circuit. During "stand-by" periods, this latter tube can be connected either as a class *A* audio amplifier to operate a loudspeaker, or as a relay amplifier to actuate the sensitive calling relay of the selective bell ringing apparatus. When the carrier equipment is in use during a conversation, tube *V-3* can be used if necessary as an audio amplifier in connection with the voice operated control circuits. For simplification, the relay and associated circuits for making these connections are not shown.

The automatic volume control operates so that an increase in detector plate current caused by an increase in the received signal level results in a corresponding increase in voltage drop across resistor *R-1*, which is in series with the detector cathode return. This voltage drop across *R-1* is applied to the rectifier tube *V-4*, in series with the high resistance *R-2*. The increase in voltage across *R-2* charges the large condenser *C-2* to a higher potential and at the same time swings the grid of the screen-grid tube *V-5* in a positive direction. This causes *V-5* to

draw more plate current through the resistor *R-3* which in turn increases the negative bias on the grid of the amplifier tube *V-1*, thereby decreasing the amplification of the signal supplied to the detector. Because of its variable amplification factor, a comparatively small change in the grid bias voltage of tube *V-1* causes a large change in the gain on this stage, the action being such that a decrease in gain takes place very quickly. An increase in gain, however, can take place only as rapidly as the charge on *C-2* decreases by leakage through *R-2*. Thus the values of *C-2* and *R-2* can be selected to obtain the desired time constant.

In operation, the volume control makes a quick adjustment of gain at the beginning of the first quarter impulse received, and unless there are intervals of longer than approximately 30 sec between following impulses, the gain established is maintained practically constant throughout a conversation. In practice, it has been found that the circuit will provide an essentially constant audio output level for variation in carrier input level of approximately 40 db, which is sufficient to take care of the maximum variations usually encountered.

In addition to its functions as a volume control and a carrier frequency amplifier, tube *V-1* also serves as a receiver blocking tube. During operation of the transmitter the screen grid of this tube, which normally is maintained at a positive potential of 100 volts, is connected to a negative point in the voltage divider by means of relay contacts located on another unit. This action effectively blocks the receiver and prevents any of the transmitted signal from appearing in the receiver output.

A full wave rectifier of the mercury vapor type is used to provide all plate and grid bias voltages. As shown in Fig. 3, all carrier frequency portions of the circuit are enclosed in an aluminum shield with separate compartments for the filter, carrier frequency amplifier, and demodulator circuits.

Duplex Control and 2-Wire Extension Units. The duplex control and 2-wire extension equipment form an essential part of all duplex assemblies. They comprise the third and fourth shelves from the top of the assembly shown in Fig. 1. Electrically, these 2 units are associated closely with each other and with practically all parts of the complete circuit.

One of several unusual features of these circuits is the method used to obtain a speech signal delay. Since cost, complexity, and space limitations prohibited the use of electrical delay network, search for a suitable method of delay was confined largely to some of the simpler forms. After considerable development, a device based upon the principle of the Poulsen telegraphone finally was selected. This mechanism is incorporated in one of the units shown in Fig. 6. It consists essentially of an accurately machined disc of insulating compound mounted on the shaft of a small induction motor and wound along its cylindrical edge with a single layer of hard steel wire. Two small coils with suitably shaped pole pieces mounted in close proximity to the periphery of the disc respectively record and reproduce a magnetic record in the steel wire. The audio signal appearing at the terminals of the pick-up coil is similar to the original impressed on the wire by the recording coil, except that it is delayed by the interval of time required for a point on the disc to travel from the recording to the pick-up coil. A small permanent magnet then erases the record and reestablishes the proper magnetic status of the steel wire necessary for continuous operation.

Within the limits of signal levels used, the device has negligible amplitude distortion. The frequency characteristic, which is largely a function of the peripheral speed of the steel band, inherently drops off at the higher audio frequencies, but with a comparatively simple equalizer a sufficiently uniform characteristic between 300 and 3,000 cycles readily can be obtained. The over-all attenuation of about 20 db is recovered in a 2-stage amplifier forming part of the same unit.

The schematic block diagram, Fig. 7, illustrates the essential circuit and operations involved in the

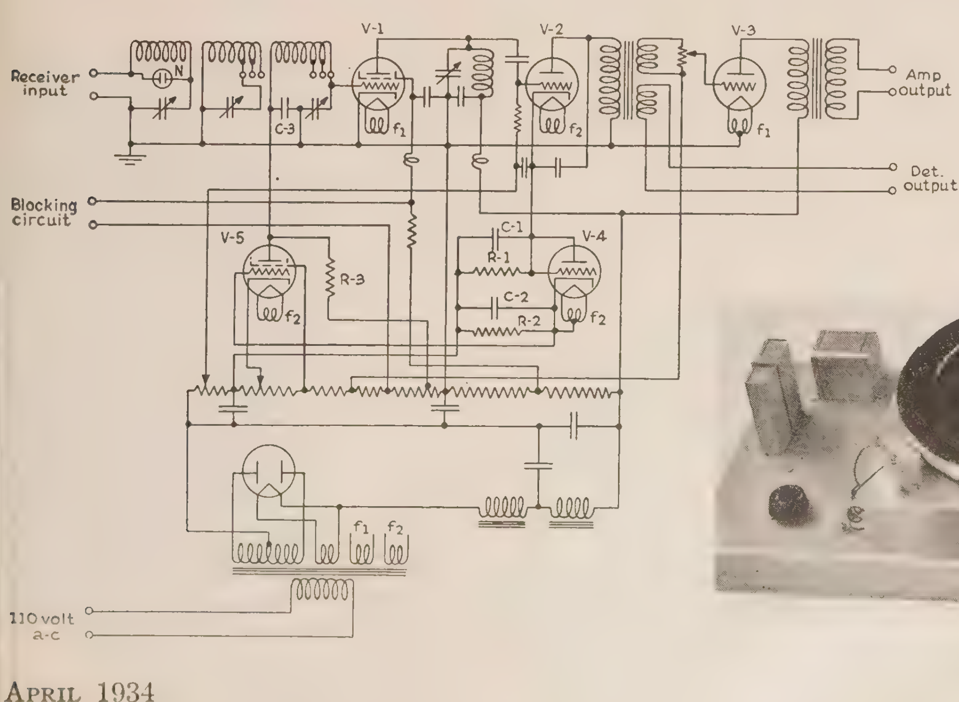

Fig. 5 (left). Schematic diagram of receiver unit

Fig. 6 (below). Speech delay unit

duplex equipment during transmission and reception. The circuit as shown represents conditions when there are no signals being transmitted or received. During transmission, the voice signal originating at the connected telephone set passes through transformer *T-2* and the contacts of relay *R-1*, and then divides between amplifiers *A-5* and *A-8*. That part of the signal passing through amplifiers *A-8* and *A-9* causes relay *R-2* to operate. Operation of *R-2* closes 2 pairs of contacts, one of which starts the master oscillator through the master oscillator control tube, and thus causes the carrier wave to be transmitted, while the other contacts block the receiver in the carrier frequency amplifier stage.

The path taken by the voice signal through amplifiers *A-5* and *A-6* leads to the delay mechanism, where a delay of approximately 0.04 sec is introduced. From the pick-up of the delay mechanism the signal then passes through amplifier *A-7*, contacts of relay *R-1*, speech amplifier *A-1*, and then to the modulator system where it modulates the carrier previously started.

During reception, the received carrier frequency signal passes through the input filter and the carrier frequency amplifier to the detector, where it is demodulated in the usual manner. The audio signal output of the detector divides between amplifiers *A-2* and *A-4*. The amplified output of *A-4* operates relay *R-1*, thereby opening the input to amplifiers *A-1*, *A-5*, and *A-8*, and connecting the output of amplifier *A-7* to the telephone line. The circuits thus are prepared by the time the delayed signal reaches the telephone line through amplifiers *A-4* and *A-6*, the delay mechanism, and amplifier *A-7*.

The relay amplifiers *A-3* and *A-9* contain 3-element hot-cathode mercury-vapor tubes which operate the associated relays *R-1* and *R-2*. These tubes must operate on a d-c plate supply, and therefore require a third tube of that type operating on alternating current to cut them off when the voice signal falls below a certain minimum level. The large amount of power obtained from these tubes permits the use of standard quick-acting relays of rugged design. These relays are made slightly slow to release to assure that the ends of the delayed signal will not be lost. Quick pull-in is retained by shunting the winding of each relay with a small copper oxide rectifier.

Since the telephone line never is connected to both transmitter and receiver circuits at the same time, there is no need for a hybrid balance circuit. The only adjustments necessary are those of signal level input to the carrier transmitter. Where both long and short telephone extensions are connected to the same equipment, the adjustments of the amplifiers in the control units are set up for the longest extension. For the shorter extensions, a variable attenuation pad automatically is cut into the circuit by relays in the relay unit.

Relay Units. The 2 relay units, one for simplex and one for duplex operation, centralize the majority of all switching functions involved in starting and stopping, receiving and placing calls, and in ringing and switching extension circuits. Their mechanical construction differs slightly from that of the other main units in that provision is made to accommodate subunits or attachment units as required by each individual installation.

One arrangement of the duplex relay unit is shown as the second shelf from the top of the assembly illustrated in Fig. 1. The right-hand half of the unit contains the parts that are common to all of the different arrangements. It includes a full wave Tungar rectifier for supplying a d-c potential of 48 volts to the relay and telephone circuits, and for generating the 400-cycle dialing tone. The left-hand section contains the relays, rotary switch selector, and other auxiliary parts to provide selective bell ringing and full control from a remote point. The relays and selector switch used are standard automatic telephone parts. For convenience in inspection and maintenance they are mounted in a group on a removable subbase.

Provision is made for 4 2-wire extension circuits that can be connected directly to standard 2-wire central battery telephones or through private branch exchange boards to a large number of extensions. Any one of the 4 extensions can be wired for pre-

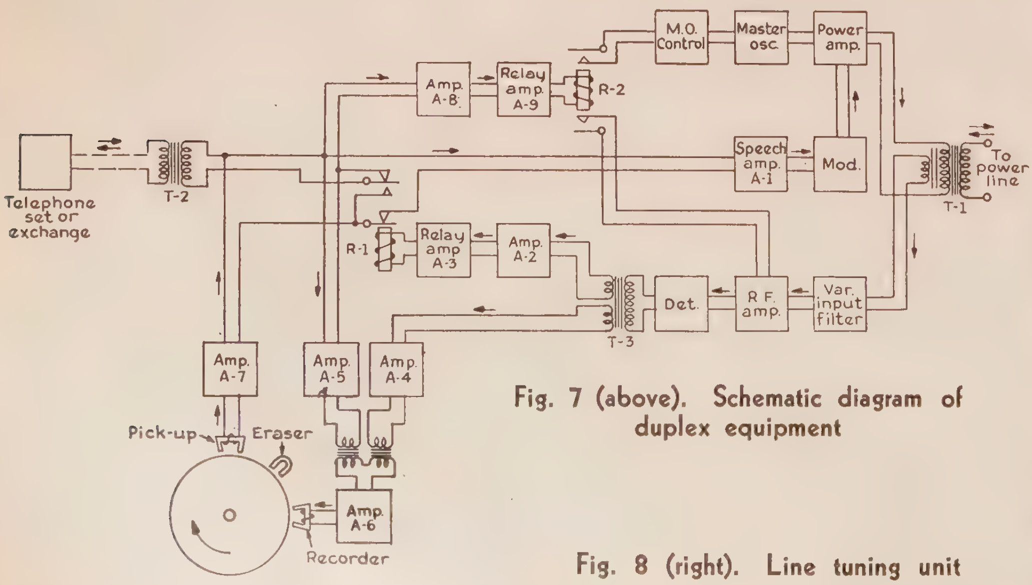

Fig. 7 (above). Schematic diagram of duplex equipment

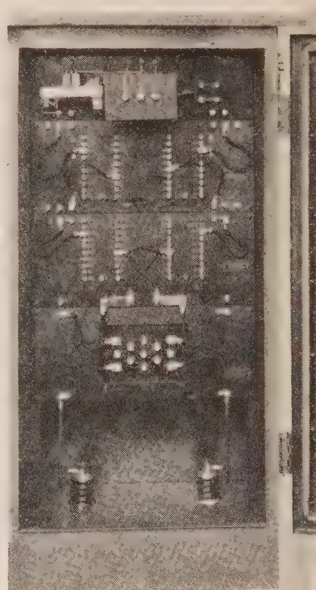

Fig. 8 (right). Line tuning unit

ferred service so that if desired a power system load dispatcher can break in on a conversation to obtain the use of the carrier channel. Extensions not connected for preferred service are normally locked out and receive a busy tone when an attempt is made to use the carrier channel already in use by other stations or by another extension of the same station.

The selective ringing circuits are designed to respond only to dial impulses and, therefore, voice signals cannot cause false rings or excessive wear of the relays and selector mechanism.

An alternative and relatively simple relay arrangement for duplex operation provides one local telephone circuit with a loud speaker for reception of calls. This circuit can be extended through a private branch exchange board or interconnected to another extension circuit, but it is necessary for a local operator to set up these connections and supervise the incoming and outgoing calls.

The simplex relay unit performs functions for the simplex assemblies similar to those described for the duplex combinations except that the simplex method of operation inherently prevents interconnection with standard telephone circuits. The simplest arrangement in this case provides for local 6-wire extensions with loudspeaker reception of calls. Control and operation over 2-wire extensions from remote points can be provided by adding a simple attachment to this unit and using special extension equipment at the remote end. Selective ringing, where required, can be added also by means of a second attachment.

Cabinet. The standard cabinet used for all simplex and duplex assemblies is illustrated in Fig. 1. It has a width of only 36 in., a depth of 18 in., and an over-all height of 78 in. The steel angle framework arranged to accommodate 6 shelf units is fastened to the top and bottom so that the weight of all shelf units is carried directly to the floor through feet beneath the supporting frames. For combinations requiring more than 6 units, 2 cabinets are bolted together side by side. All external connections including lead-ins from the coupling equipment are brought in through knockouts in the bottom of the cabinet.

Line Tuning Equipment

Where carrier equipment is applied to some of the higher voltage transmission systems, the cost of the coupling capacitors often represents a considerable portion of the investment. It is therefore important that the capacitors be used as efficiently as possible. Considerable economy is effected by using the same coupling capacitors as a source of potential for operating certain instruments and relays, and for several carrier channels.

To meet these requirements, as well as those of a large variety of coupling circuit conditions, the unit principle also has been applied to the tuning equipment. Figure 8 shows one arrangement of units in a standard weatherproof cabinet. Other combinations of standard tuning panels are used to tune one set of coupling capacitors for 1, 2, or 3 carrier frequency channels involving one or more transmitter-receiver assemblies at the same location.

A New Type of Warble Tone Generator

In testing various types of apparatus used in electrical communication circuits, it is often desirable to obtain a single average reading over a range of frequencies. For this purpose a "warble" tone, or a tone the frequency of which varies cyclically over the desired range, is used. In this paper is described a new type of electronic tube warble tone generator which utilizes a "relaxation" oscillator and has no mechanically moving parts.

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MUSIC or the human voice has so irregular a wave form that it is not satisfactory for use in many tests of units that enter into the construction of various communication systems. If either the frequency or intensity of an electric wave is changing constantly, the deflections of the meters in a test circuit using this wave are too unstable to be read accurately. Although an "over-all" characteristic can be obtained by testing a unit with one frequency at a time and plotting a frequency curve, it is often desirable to get a single average reading for a range of frequencies. For this purpose a tone having a pitch that varies regularly over the desired frequency range is needed.

Such a tone has been called a warble tone and usually is produced by an ordinary vacuum tube oscillator having the inductance or capacitance of its tuned circuit varied cyclically by mechanical means. This article describes a new type of warble tone generator having no mechanically moving parts and having a wide flexibility of control. In the many uses of thermionic vacuum tubes one of the common methods of obtaining controlled variation of some factor in an electric circuit is to control the current through a resistor by means of a triode relaxation oscillator. The variable voltage produced across the terminals of this resistor then may be used to control the circuit. Such a system is used in the unit described in this paper.

A generator of this kind has been designed and constructed in the communication laboratories of the

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electrical engineering department at the University of Maine (Orono). It is being used to supply a warble tone for regular student laboratory experiments in testing telephone transmitters, receivers, subsets, transformers, and other apparatus.

Construction and Operation

The new warble tone generator consists of 4 parts: (1) a constant radio frequency oscillator, (2) a second oscillator, the radio frequency of which is controlled by a relaxation oscillator, (3) a detector and amplifier, and (4) a power supply unit. The constant frequency oscillator produces 250 kc per second. This wave is combined with the variable frequency output of the second oscillator to produce a beat of variable audio frequency. The detector, together with an additional stage of amplification, raises the power of the audio wave to a level suitable for laboratory test purposes. The frequency of the second oscillator is made to fluctuate by "warbling" or varying its grid bias. This is accomplished by allowing the current drawn by a relaxation inverter to pass through the grid biasing resistor of the oscillator.

Referring to the accompanying connection diagram, Fig. 1, the constant frequency oscillator is seen in the upper left-hand corner. A type 227 tube is used operating in the well-known series-fed Hartley circuit. Condenser C_1 and coils L_1 and L_3 comprise the tuned circuit, which resonates at 250 kc. Coil L_2 takes some of the high frequency power from the tuned circuit and delivers it to opposite corners of the 4 resistor net composed of R_1, R_2, R_3, and R_4. The other 2 corners of this net are connected to the pick-up coil of the other oscillator. This resistor arrangement reduces the coupling between the 2 oscillators, and hence, decreases the tendency for them to pull into step. Condenser C_2 has a value of 0.5 μf and is used as a by-pass.

The second oscillator (lower left-hand corner of diagram) also uses a type 227 tube and the Hartley circuit. The variable tuning condenser C_9 furnishes a means of adjusting the frequency. The fluctuating grid bias for this oscillator is supplied by a variable IR potential drop across the upper end of resistor R_{10} (explained later) plus the fixed IR drop across resistor R_{14}. It should be noted that the cathode of this tube is grounded. Condensers C_{10} and C_{11} are by-pass condensers for the d-c plate and grid potentials, respectively. Voltmeter V registers the grid bias.

In the lower central part of the diagram is the relaxation inverter T_5. This is a type *FG*-17 "thyratron" tube (mercury vapor filled). The principle of operation is somewhat different from that of the ordinary vacuum tube oscillator. A condenser, C_{12}, is charged through a resistor R_{12} from the output of the rectifier. When the charge on this condenser or the voltage across its terminals has reached a certain point the condenser is discharged quickly through the plate circuit of the tube. The point at which this action takes place is determined by the grid bias of the tube. Consequently, the condenser continues to charge and discharge at a rate depending also upon its size and the size of the series resistor R_{12}.

The complete d-c charging circuit may be traced from resistor R_{13} (plus terminal of the rectifier unit) to resistor R_{12} and the plate circuit of tube T_5. The charging current then returns to the rectifier from the filament of T_5 through resistors R_{11} and R_{10}. The wave form of this current is triangular, which means that the current varies linearly with time. The inductance L_8, in series with the discharge circuit, undoubtedly decreases the peakedness of the wave form. At first, this feature might seem objectionable since it alters the uniformity of the saw tooth wave form; however, the author has found that the presence of a small amount of inductance at this point produces a warble tone more pleasing to the ear as far as smoothness is concerned.

In actual use the frequency of relaxation inverter tube T_5 is adjusted by means of the sliding contact on resistor R_{11}. At the instant when condenser C_{12} starts to charge the current flowing is large. Consequently, the voltage drop across R_{11} holds the grid voltage of the inverter tube sufficiently negative to prevent tube conduction until the condenser has acquired its charge. By moving the slider on R_{11} downward (see Fig. 1) the condenser is not allowed to acquire such a large charge before it is discharged, and so the cycle of operation is completed in less time. A variation of the relaxation frequency from 1 to 40 cycles per second readily can be obtained by this adjustment. A switch is provided in the plate lead to stop oscillations of the inverter so that a steady tone may be produced by the generator if desired.

The detector tube T_2 has as its grid excitation the IR potential drop across R_3 of the resistor net. This IR drop is a result of the combined output of the two radio frequency oscillators. Resistor R_5, by-passed by condenser C_3, insures the proper bias on this tube. The plate circuit of the detector is resistance-coupled to a pentode amplifier by means of plate resistor R_6, by-pass condenser C_5, and volume control potentiometer R_7. Condenser C_4 by-passes the radio frequency energy to ground. The pentode amplifier is choke-coupled to an output transformer as shown. Grid bias for this tube is obtained by means of resistor R_9 connected between ground and the center tapped resistor R_8 across the filament.

The power transformer P_3 with the 2 half-wave rectifier tubes, T_6 and T_7, supply the necessary d-c power through the filter composed of choke L_9 and condensers C_{13} and C_{14}. Variable resistor R_{14} furnishes a means of adjusting the average value of the grid bias of the variable frequency oscillator tube T_4. This resistor carries the steady d-c current returning from the plate circuits of all the tubes except that of the relaxation inverter. Consequently, the common ground potential can be raised to any desired point above the potential of the negative terminal of the d-c power supply (center tap of high voltage winding on power transformer). This resistor also carries the direct current supplied by the grid of the oscillator in question.

In the following discussion the practically constant d-c voltage across resistor R_{14} will be desig-

nated as $-E_{14}$ (the minus sign signifying that the minus terminal is connected toward the grid of tube T_4). To this voltage ($-E_{14}$) must be added the d-c voltage E_{10} (across the upper part of R_{10}) to obtain the total applied grid bias for T_4, that is: $E_g = -E_{14} + E_{10}$. It already has been pointed out that E_{10} varies according to the oscillations of the inverter since R_{10} carries the varying direct current from the inverter. Denoting the maximum change in E_{10} as E_c, it is evident at once that the voltage E_g applied to the grid of T_4 varies from ($-E_{14} + E_{10}$) to ($-E_{14} + E_{10} + E_c$). This variation produces a small fluctuation in the output frequency of T_4 and, hence, a large swing or variation in the frequency of the resulting audio wave. To illustrate this, suppose a warble wave varying between 400 and 700 cycles per second is being produced. If the fixed oscillator is producing 250,000 cycles per second, then the frequency of the other oscillator can be varying from 250,400 to 250,700 cycles per second. This is a variation of 0.12 per cent, which is very small.

The variation of the frequency of a Hartley oscillator due to change in grid bias probably is due to the change in the internal operation of the tube. Changing the grid bias changes the current drawn by the grid. This, no doubt, changes the potential distribution among the electrodes which alters the effective internal plate and grid resistances. Since the frequency of the oscillator does not depend entirely on the values of inductance and capacitance used in the tuned circuit, a small variation can be obtained by changing the tube characteristics.

By setting the slider of R_{10} at its upper position the grid voltage of T_4 can be made to swing as much as 15 volts. Under this condition it is possible to vary the output of the generator over the entire audio range when a low warble frequency from the inverter is used. For testing purposes a warble frequency of at least 10 cycles per second is desirable since with a lower frequency the pointers of any meters in a test circuit may vibrate over too wide a range to be readable. The oscillogram shown in Fig. 2 was taken with a warble frequency of 60 cycles per second. The audio frequency of the warble waves varies from 620 to 860 cycles per second; the upper wave is a 60-cycle timing wave.

Considerable time was spent in trying to obtain a good wave form of output audio frequency. All the voltages on the detector and amplifier had to be adjusted to rated values, and then the coupling of the radio frequency pickup coils L_2 and L_6 had to be adjusted to obtain as much undistorted power output as possible. Loose coupling between the coils for each radio frequency oscillator, of course, tended to decrease harmonics. Since the oscillators had a tendency to pull into step when a low audio frequency beat was being produced, they were shielded separately as indicated by the dashed lines on the diagram. The oscillogram of Fig. 3 shows the wave form of the generator at 150 cycles per second with the warble effect not in use.

The output transformer P_1 is quite necessary with the type 247 pentode amplifier in order to match any practical load impedance to the plate impedance of the tube. An undistorted output of 1 watt readily can be obtained by this means. The voltage variation of the output is very small over a wide frequency range in the central portion of the audio band. For very high and low frequencies the voltage decreases somewhat.

Method of Adjustment

For ordinary student laboratory use the necessary adjustments are made while the operator listens

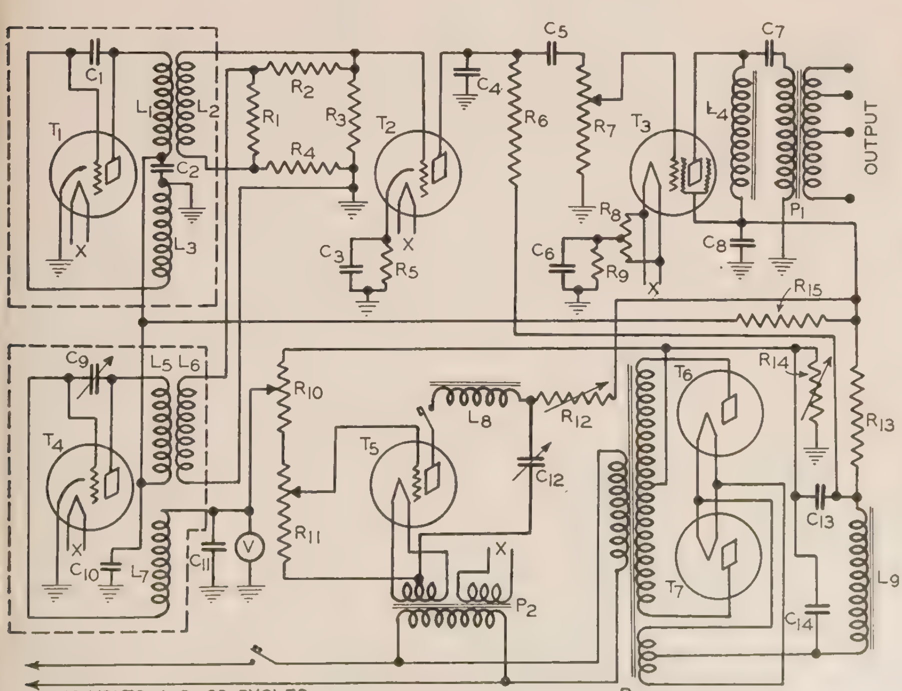

Fig. 1. Connection diagram of the warble tone generator

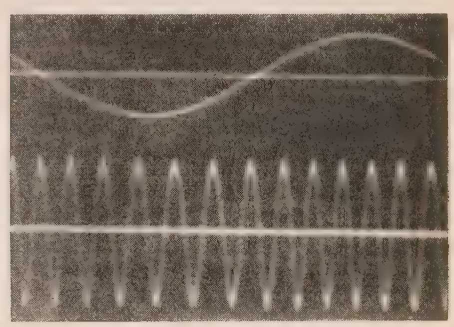

Fig. 2. Output of the warble tone generator showing a frequency sweep of 620 to 860 cycles per second

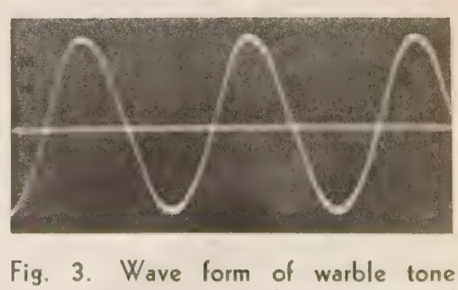

Fig. 3. Wave form of warble tone generator at 150 cycles per second (warble effect not in use)

to the output applied to a loud speaker. The circuit is allowed to warm up for about 30 minutes. After this the average value of the tone first is adjusted roughly by means of condenser C_9 to the desired range—high, medium, or low frequency range. The frequency of warble then is adjusted by means of potentiometer R_{11} to a suitable value. The amount of swing or variation of the output frequency is adjusted by potentiometer R_{10}. Final adjustment is obtained by additional manipulation of these 3 controls.

The d-c voltmeter V, which registers the grid bias of the variable frequency oscillator, gives a visual check on the warble action. Although the pointer of the meter cannot follow the voltage fluctuations exactly, its vibration does give a good indication of the warble frequency and warble sweep when the former is not too high.

Of course, it is impossible to adjust the generator output exactly to any desired audio range by this method of judging by ear. Until the circuit is perfected to a higher degree, it would be extremely difficult to calibrate the dial settings to any high degree of accuracy because the stability of operation is dependent on the constancy of the supply voltage.

To adjust the audio range more accurately an oscillograph may be used to compare the warble output to the output of a fixed oscillator producing a known frequency.

The range of the audio output can be shifted easily and quickly from a low pitch warble to a high pitch warble or *vice versa* by the adjustment of the tuning condenser C_9. This does not affect the frequency of warble swing. The magnitude of warble swing in cycles is approximately constant for any setting of R_{10} regardless of the range being produced. This means that for a low warble tone the percentage swing is much greater than for a high warble tone. Usually the setting of R_{10} also is changed when a different audio range is obtained.

As mentioned previously, the power output can be adjusted by volume control potentiometer R_7. Resistor R_{14} is manipulated to give an average bias on tube T_4 of from 10 to 20 volts, indicated by the voltmeter. For ordinary use condenser C_{12} and resistor R_{12} need not be altered.

Wide-Band Open-Wire Program System

Radio programs are regularly transmitted between broadcasting stations over wire line facilities furnished by the Bell System. Both cable and open wire facilities are employed for this service. Recently a new program transmission system for use on open wire lines has been developed which has highly satisfactory characteristics. A description of this open wire system and test results obtained with it are given in this paper.

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THE SIMULTANEOUS broadcasting of the same radio program from a large number of broadcasting stations, in different sections of the United States, has become of such every-day occurrence that the radio listening public takes it as an accepted fact and in many cases does not know whether the program is originating in the studio of a local broadcasting station or in a broadcasting studio in some distant city. The wire line facilities furnished by the Bell System for the interconnection of the radio stations, particularly the wire line facilities in cable, have such transmission characteristics that little detectable quality impairment is introduced even when programs are transmitted over very long distances.

This cable program system was described in a recent paper. (See "Long Distance Cable Circuit for Program Transmission," by A. B. Clark and C. W. Green, A.I.E.E., TRANS., v. 49, 1930, p. 1,514–23.) More recently a new program system for use on open-wire lines, which possesses transmission characteristics comparable with the cable system, was developed and an extensive field trial made involving 2 circuits between Chicago and San Francisco. This paper describes this new open-wire program system and gives the principal results of the tests made on the 2 transcontinental circuits.

In the paper referred to describing the cable system, the various factors and considerations involved dictating the grade of transmission performance that is desired for program circuits were discussed in considerable detail so they will not be reviewed here. The transmission requirements chosen as objectives are as follows:

Frequency Range. Frequency range to be transmitted without material distortion: about 50 to 8,000 cycles.

Volume Range. Volume range to be transmitted without dis-

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tortion or material interference from extraneous line noise: about 40 db, which corresponds to an energy range of 10,000 to 1.

Nonlinear and Phase Distortion. Nonlinear distortion with different current strengths and phase distortion to be kept at such low values as to have negligible effect on quality of transmission even on the very long circuits.

The frequency range afforded by the new open-wire program circuits extends about 3,000 cycles higher and more than 50 cycles lower than the frequency range available with the open-wire program circuits previously used. (See papers: "Wire Line Systems for National Broadcasting," by A. B. Clark, presented before the World Engineering Congress at Tokio, Japan, October 1929, and published in I.R.E., *Proc.*, v. 17, 1929, p. 1,998–2,005; and "Telephone Circuits for Program Transmission," by F. A. Cowan, A.I.E.E. Trans., v. 48, 1929, p. 1,045–9.) The extension of the frequency range at the upper end necessitates the sacrifice of one carrier telephone channel of carrier systems operating on the same wires with the program pair since the frequency band of the lowest carrier channel lies in this range. In order to minimize noise and the possibility of crosstalk, the phantoms of program-pairs are not utilized and, of course, d-c telegraph compositing equipment is removed in order that the proper low-frequency characteristics may be realized.

Description of New Open-Wire System

In general, the amplifiers on the open-wire program circuits employ the same spacing as the telephone message circuit repeaters on the same pole lead. The average repeater spacing is about 150 miles but the repeaters may be located as close as 60 miles or may be as much as 300 miles apart depending upon the location of towns and cities on the open-wire route and the gauge of the wires used. The upper diagram of Fig. 1 shows a typical layout of the new wide-band open-wire program system. Three types of stations are shown, a terminal transmitting station, an intermediate station which may be either bridging or nonbridging, and a terminal receiving station.

The terminal transmitting station includes an equalizer for correcting for the attenuation distortion of the local loop from the broadcasting studio, an attenuator for adjusting the transmission level received from the local loop to the proper value, an amplifier for inserting the required gain, filters for separating the program and carrier channels, monitoring amplifier, loudspeaker and volume indicator for making the necessary operating observations, and a predistorting network and associated amplifier.

At the intermediate station are included line filters for separating the carrier currents and program currents and directing them to their proper channels, 2 adjustable attenuation equalizers for correcting for the attenuation distortion of the line wires and associated apparatus, gain control attenuator, line amplifier, and associated monitoring equipment. At intermediate stations where it is necessary to provide branches to radio stations or to other program circuits an amplifier of a special type having several outlets is inserted immediately in front of the line amplifier.

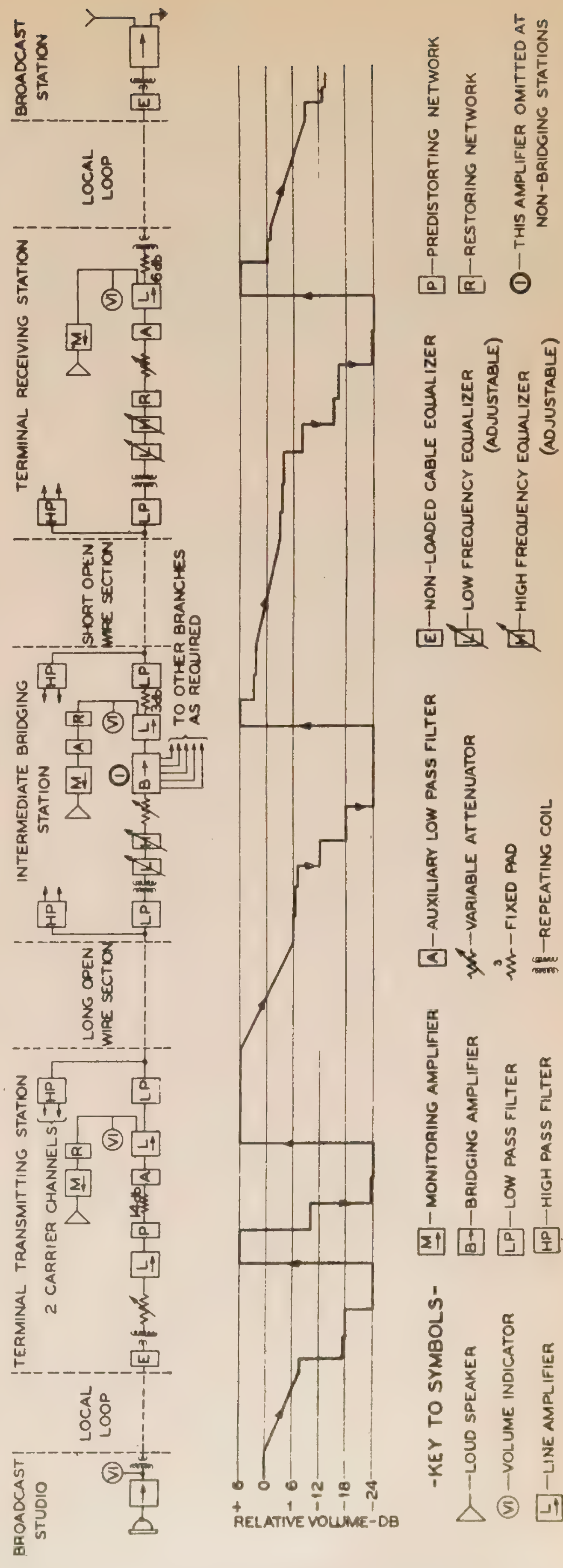


Fig. 1. Typical circuit layout and level diagram of the new wide-band open-wire program system

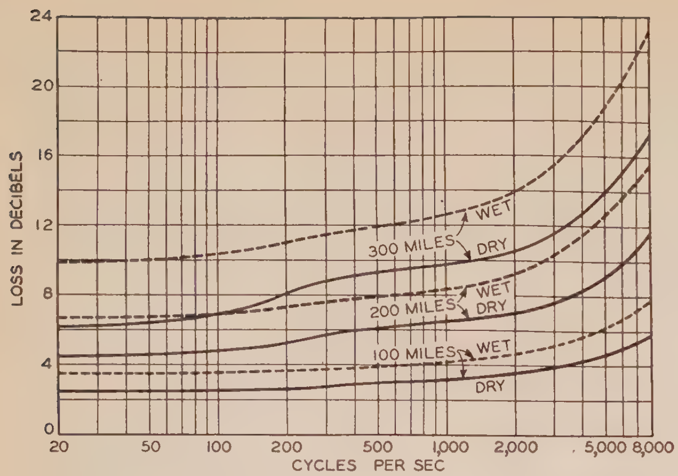


Fig. 2. Insertion loss of 165-mil 8-in. spaced circuits

At a receiving terminal, the layout employed is very similar to that utilized at intermediate stations except that an additional low pass filter and a restoring network are inserted ahead of the receiving amplifier.

A novel feature is provided in this program system for minimizing its susceptibility to interference at higher frequencies. It consists in predistorting the transmission at the sending end of the circuit so that currents above 1,000 cycles are sent over the line at a higher level than if this arrangement were not employed, thus increasing the signal-to-noise ratio at these frequencies. Such an increase in power at high frequencies is permissible without overloading in the line amplifiers in view of the fact that the energy content of the program material above 1,000 cycles is materially less than at the low frequencies, and decreases rapidly as the frequency is increased. In order to restore the program material to the same relations it would have if it were not predistorted, a network is inserted at each point in the branches which feed the radio stations and at the receiving terminal. This network introduces attenuation and phase distortion which are complementary to those introduced at the sending end of the circuit by the predistorting network. The net reduction in high frequency interference is equal to the discrimination introduced by the predistorting network in favor of these frequencies, and is therefore equal approximately to the loss of the restoring network at the same frequencies.

In the lower part of Fig. 1 is shown a level diagram, from which may be noted the losses and gains introduced by different parts of the system at a frequency of 1,000 cycles. The maximum volumes which are permitted in the various parts of the system are also indicated approximately by this diagram.

Line Facilities

As is well known the open-wire lines employed in telephone and program service do not have uniform attenuation for all frequencies, the low frequencies being transmitted with much less loss than the high frequencies. Since the program circuits employ the same type of open-wire facilities that is used in the message circuits, 3 different gauges of wire with either of 2 pin spacings between wires may be used and the repeater sections may vary in length from 60 to 300 miles. This means that the attenuation frequency characteristic of a repeater section not only varies with frequency but also varies considerably in magnitude of attenuation depending upon gauge and length of repeater section.

On Fig. 2 are shown 3 pairs of characteristics which illustrate the loss-frequency characteristics of 3 lengths of 165-mil, 8-in. spaced circuits. The lengths chosen for purposes of illustration are 100, 200, and 300 miles, respectively. The solid line curves show the insertion loss-frequency characteristics of the circuits for average dry weather conditions when the circuits are connected between 600-ohm resistances. The dashed line curves indicate the wet weather insertion loss characteristics, that is, they indicate the loss-frequency characteristic which might obtain if the lines were very wet for the entire length of a repeater section.

For the purpose of comparing the attenuation-frequency characteristics of the different types of open wire lines, the curves shown on Fig. 3 have been prepared. These characteristics have been plotted so that all coincide at 1,000 cycles; thus a direct comparison of the difference in shape of the

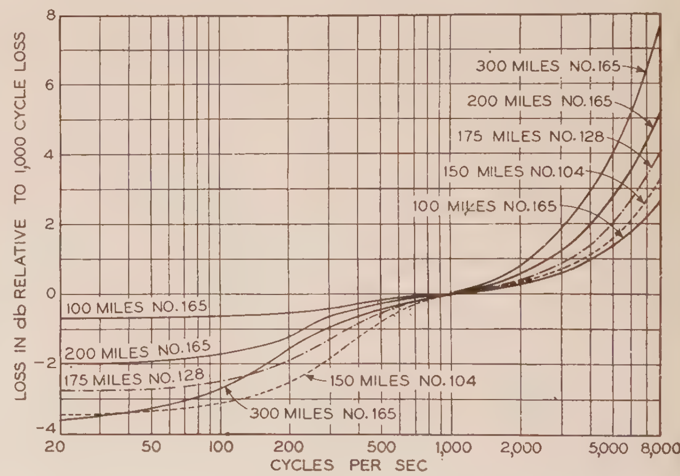


Fig. 3 (above). Attenuation-frequency characteristics of open-wire lines when inserted between 600-ohm resistances

8-in. spaced pairs

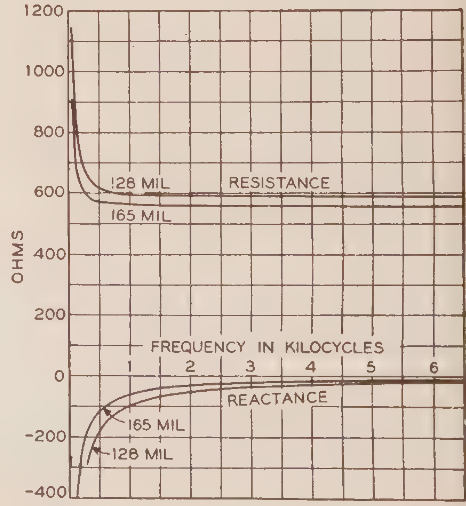


Fig. 4 (right). Impedance of 8-in. spaced pairs

attenuation frequency characteristics may readily be observed.

In Fig. 4 are shown resistance and reactance components of 165-mil and 128-mil 8-in. spaced open-wire lines. Note that, except at low frequencies, the impedances of the various open wire lines are quite uniform throughout the frequency range and do not depart greatly from 600 ohms. For this reason and in consideration that the majority of telephone apparatus is designed for 600-ohm impedance, all units of this new program system, except the carrier line filters, have been designed to have an impedance of 600 ohms. In order to reduce reflection losses, particularly in the carrier range, the line filters have been designed to have an impedance on the line side somewhat lower than 600 ohms although the drop or office side impedance is 600 ohms.

Attenuation Equalizers

To furnish the necessary attenuation corrections for the 3 different gauges of lines, 4 adjustable attenuation correcting networks have been provided. One attenuation equalizer provides attenuation correction for high frequencies only and is common for all gauges. The 3 other equalizers provide low-frequency attenuation correction designed specifically for the particular gauge of circuit the equalizer is to be associated with and also include a fixed amount of high-frequency attenuation correction.

On Fig. 5 is shown a schematic diagram of one of the low-frequency attenuation equalizers. This consists of 4 sections of 600-ohm constant impedance type networks. One section referred to as a basic section introduces attenuation correction over the complete frequency range from 35 to 8,000 cycles for a particular minimum length of line, as for example, in the case of 165-mil circuits this is for 100 miles. The 3 other sections, on the other hand, furnish attenuation correction only for frequencies from approximately 1,000 cycles down to 35 cycles. Section 1 of the equalizer for 165-mil circuits puts in about 0.5 db more loss at low frequencies than it does at 1,000 cycles. Section 2 puts in double the amount of correction that is introduced by section 1 and section 4 introduces 4 times as much attenuation correction as section 1. These 3 sections are controlled by switches so that any one or all of them may be cut in tandem with the basic section. The attenuation corrections afforded for the various adjustments of this equalizer are shown on Fig. 6.

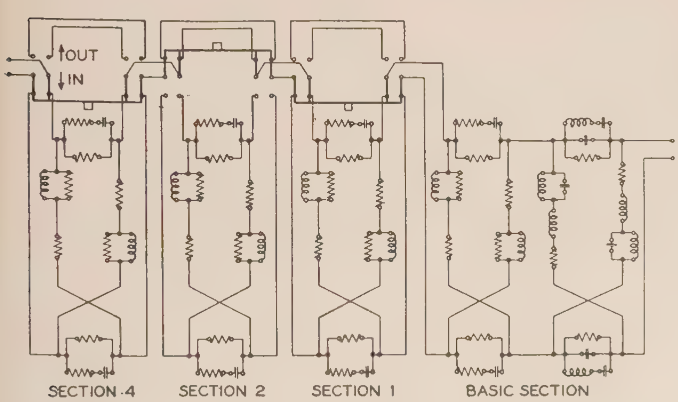


Fig. 5. Low-frequency attenuation equalizer

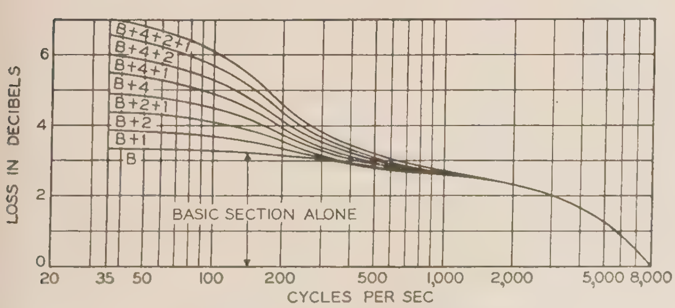


Fig. 6. Attenuation correction furnished by low-frequency equalizer for 165-mil circuits

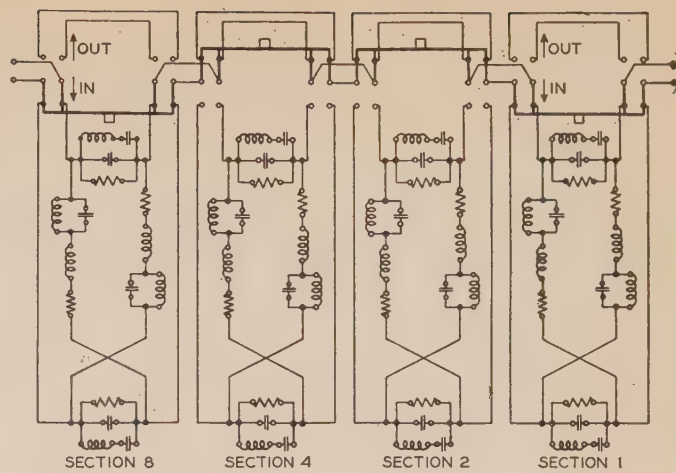


Fig. 7. High-frequency attenuation equalizer

The attenuation equalizers for 128-mil and 104-mil facilities are similar in construction to the one just described having different constants so as to furnish somewhat different attenuation correcting characteristics.

In Fig. 7 is shown a schematic diagram of the high-frequency attenuation equalizer. This consists of 4 600-ohm constant impedance type network sections which, as indicated, are controlled by switches so that any one or all of them may be cut in tandem with the program circuit as required. In Fig. 8 is shown the loss-frequency characteristics of these 4 sections. As may be noted, the loss of the various sections is practically constant over the frequency range up to 1,000 cycles, decreasing from there on to a minimum value at 8,000 cycles. Section 1, as may be noted, furnishes about 0.5-db attenuation correction. Section 2 is double that of section 1, section 4 is 4 times that of section 1, and section 8, 8 times that of section 1. These sections may be used in tandem so that attenuation correction for the high frequencies is, therefore, provided in steps of 0.5 db from zero to 7.5 db.

An illustration of how the equalizers introduce the necessary attenuation correction is given on Fig. 9. The lower curve on this figure shows the loss of a 300-mile section of 165-mil circuit. The losses introduced by the particular sections of low and high-frequency equalizers that would be required for this length of line are indicated by the cross-

hatched areas, and the total line and equalizer loss is shown by the top horizontal line. Sufficient gain is introduced by the line amplifier to annul this loss.

Amplifiers

Two types of amplifiers are provided, one of which is used as a line or monitoring amplifier and the other which is used as a means for transforming one circuit into several circuits so as to feed various branches at points required.

For certain combinations of program circuits as many as 50 amplifiers may be connected in tandem. This necessarily imposes severe requirements on the transmission performances of the amplifiers, particularly with reference to flatness of gain-frequency characteristics and phase distortion. By designing the coils used in the amplifiers so as to have very high inductances the desired phase distortion requirements were met while at the same time the necessary flatness of gain characteristic was obtained at the low frequencies.

In Fig. 10 is shown the transmission circuit of the line amplifier and monitoring amplifier. This device has a 600-ohm input and output impedance and consists of 2 stages of push-pull amplification. The potentiometer is a balanced slide wire having a continuous gain adjustment over a range of 6 db. A balanced input transformer serves to connect the potentiometer to the grids of the 2 push-pull vacuum tubes which function as the first stage of this amplifier. The first stage is connected to the second or power stage by means of resistance coupling which gives better results both as to phase distortion and low-frequency gain characteristics than if transformer or retard coil coupling were used. Resistances are provided in the grid circuits of the second stage so that the high frequency characteristic may be adjusted as required. The power tubes are connected to an output transformer which has the unique feature of providing a monitoring outlet which is not materially affected by voltages produced at or beyond the line terminals. The transformer, as may be observed, consists of 3 balanced windings arranged as in the form of the well-known hybrid coil used in 2-wire telephone repeaters, with the exception that the 2 low impedance windings are of unequal ratio, the line windings having many

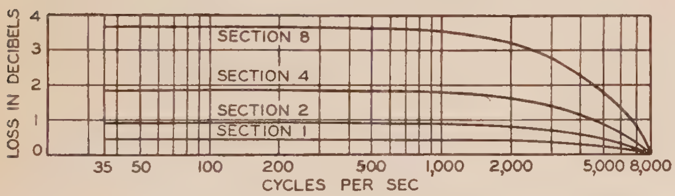


Fig. 8. Attenuation correction furnished by high-frequency equalizer

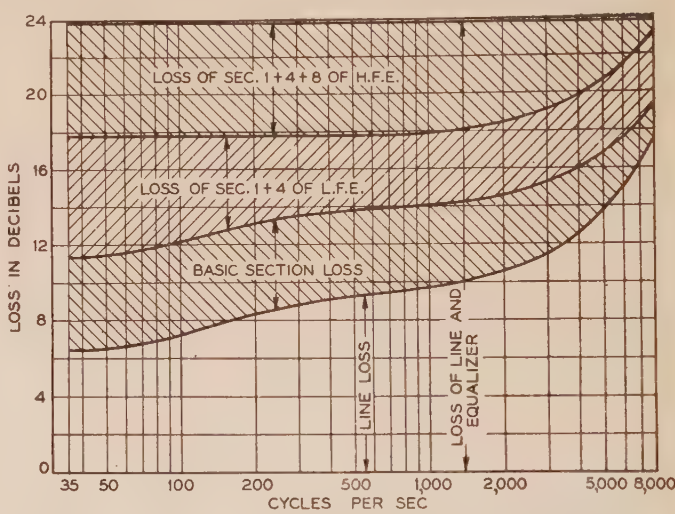


Fig. 9. Loss of 300-mile section and associated equalizers

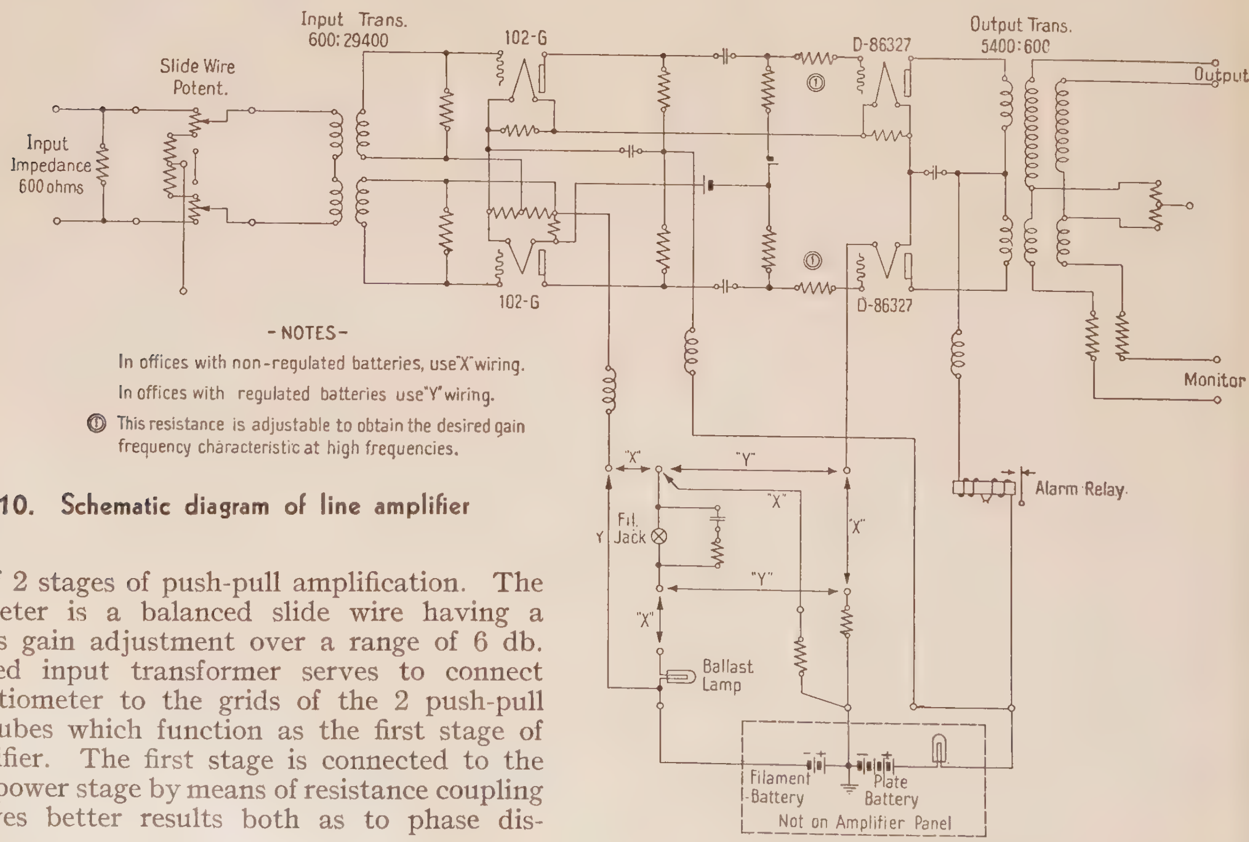


Fig. 10. Schematic diagram of line amplifier

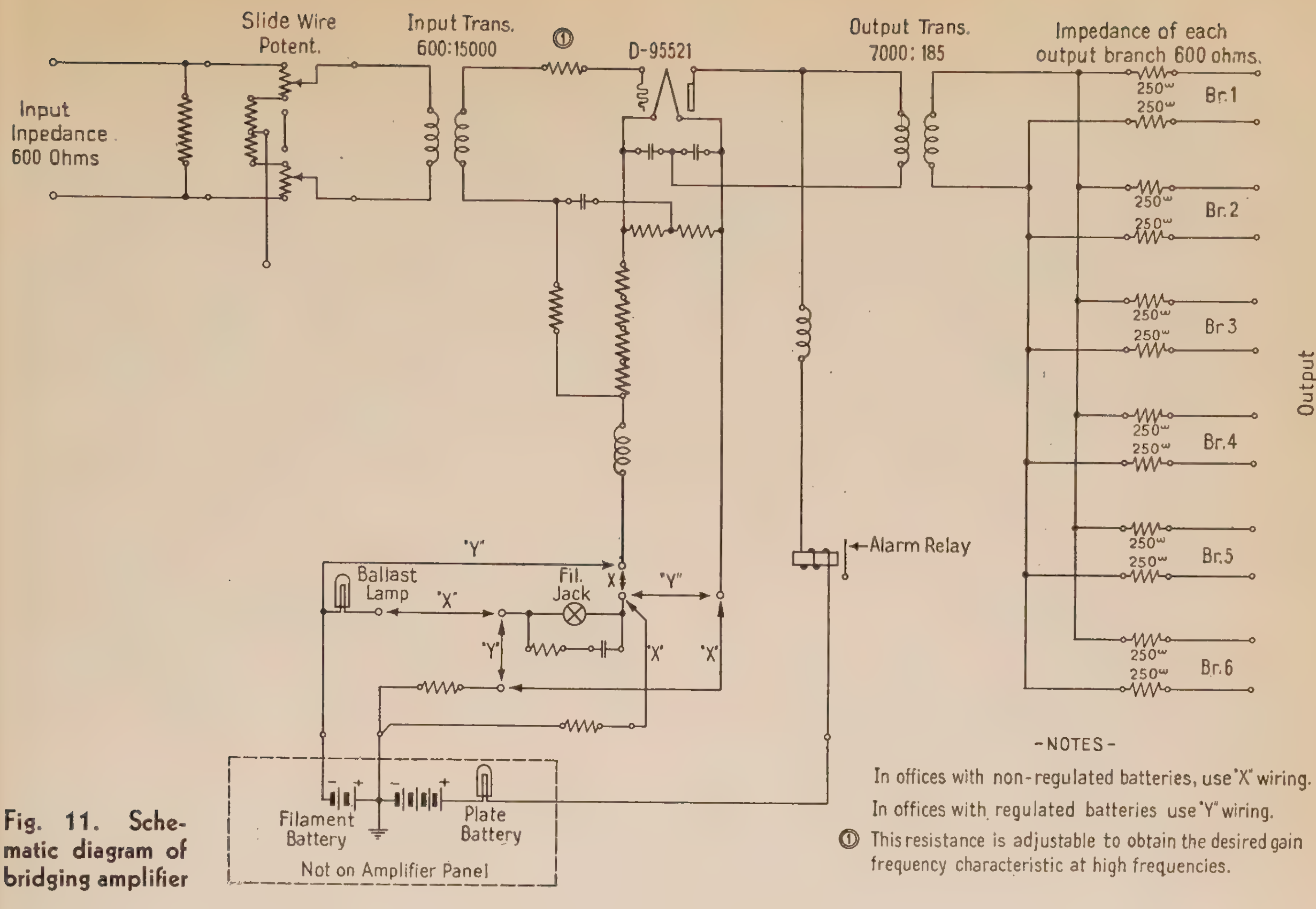


Fig. 11. Schematic diagram of bridging amplifier

more turns than the monitoring windings. The ratio of the windings is such that the voltage at the monitoring terminals when said terminals are closed through 600 ohms is 30 db below the voltage at the line terminals. Resistances are inserted in series with the monitoring winding so that an impedance of 600 ohms will be presented at the monitoring terminals.

The average gain of the amplifier with the potentiometer set at its maximum position is 33 db. Of 100 amplifiers measured, the gain at 35 cycles averaged 0.10 db less than the gain at 1,000 cycles, while from 100 to 8,000 cycles the gain was constant within 0.05 db. The delay at 50 cycles is approximately 0.6 millisec greater than it is at 1,000 cycles. From 150 to 8,000 cycles the delay is substantially constant and is only a small fraction of a millisecond. The amplifier is capable of handling an output power 9 db above reference volume without noticeable distortion.

At several points along a program circuit taps or branches are provided so as to connect various broadcasting stations to the program circuit and also to connect to other program circuits which form part of a broadcasting network. Points where such connections or branches are made are commonly called bridging stations. At some points as many as 6 branches are supplied but generally only 2 or 3 taps are utilized.

To accomplish this branching out at a bridging station a resistance network multiple is provided having 6 outlets. This network multiple is shown on Fig. 11. To annul the loss of the network a single stage amplifier is connected in front of it. This network multiple and amplifier are mounted on the same panel forming a single integral unit. The network multiple is so proportioned that if any one of the branches is accidentally opened or short-circuited the other branches are affected to only a minor degree. The amplifier is adjusted so that the gain from the input terminals to any of the output branches is zero. The bridging amplifier is normally inserted immediately in front of the line amplifier. As in the case of the line amplifier mentioned above, high inductance coils are utilized in order to keep phase distortion at a minimum. A resistance adjustment is provided in the grid circuit in order to adjust the high frequency characteristic of this amplifier to the desired value.

The gain-frequency characteristic of the bridging amplifier is practically identical with the corresponding characteristic just described for the line amplifier, while the delay is even less.

Predistortion

The means utilized to accomplish the predistorted transmission referred to earlier includes the provision of a so-called predistorting network at the sending end of a program circuit and a restoring network in each branch which supplies a broadcasting station. The predistorting network introduces a large loss at low frequencies with a decreasing loss as the frequency is increased. By introducing suitable

amplification immediately behind the predistorting network the resultant effect is to raise the high-frequency transmission relative to the low frequency transmission by the difference in loss between the 1,000-cycle loss of the predistorting network and its higher frequency loss. The restoring network characteristic is the inverse of the predistorting network. These 2 networks are 600-ohm constant impedance type structures. The restoring network is shown schematically in Fig. 12. The predistorting network is generally similar to this having different constants and a slightly different arrangement of elements. On Fig. 13 are shown the loss-frequency characteristics of the predistorting and restoring networks and a third characteristic which is the sum of these 2. As may be noted this latter characteristic has a constant value throughout the frequency range.

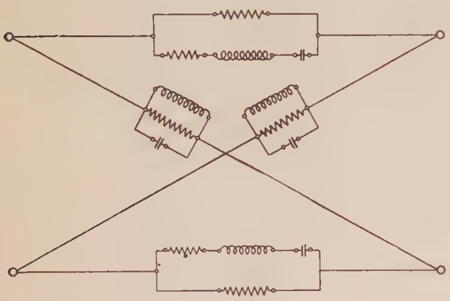


Fig. 12. Restoring network

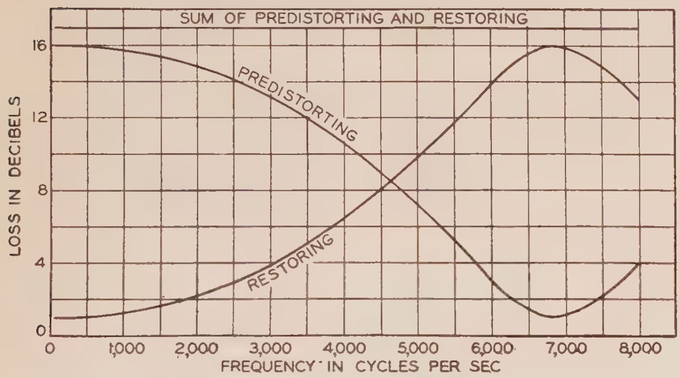


Fig. 13. Loss-frequency characteristics of predistorting and restoring networks

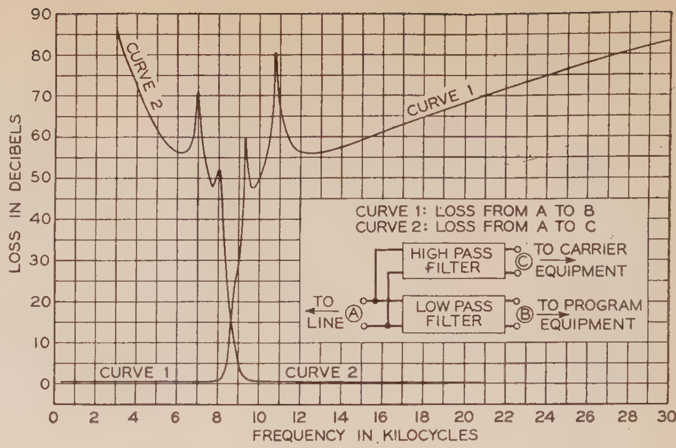


Fig. 14. Characteristics of line filter sets

Line Filters

As a rule on open-wire circuits other transmission channels are provided on the same wires which carry the program transmission. These other channels operate at frequencies above the program range and in order to direct the various currents to their proper channels at a terminal or repeater station, carrier line filter sets are inserted at the ends of the line wires. The carrier line filter sets include a low pass and a high pass filter. The low pass filter, cutting off somewhat above 8,000 cycles,

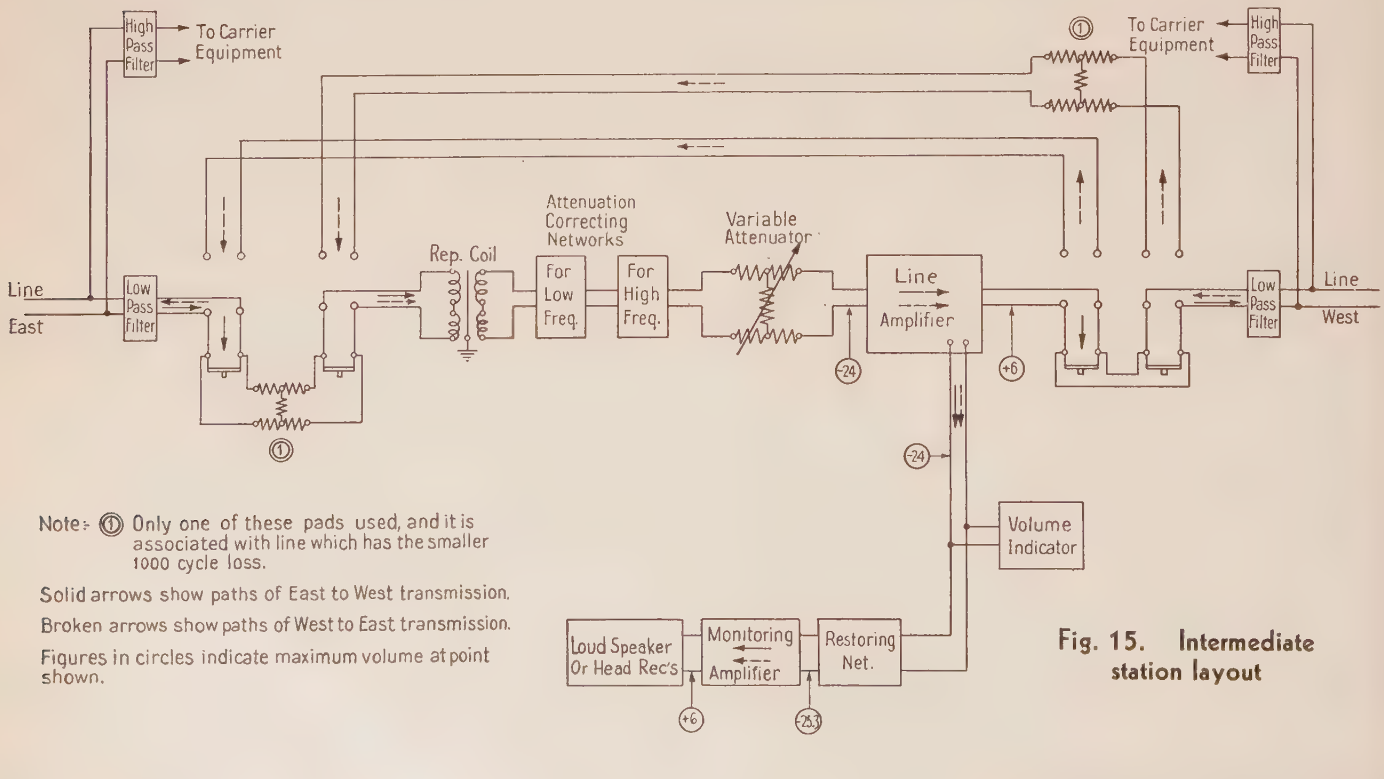
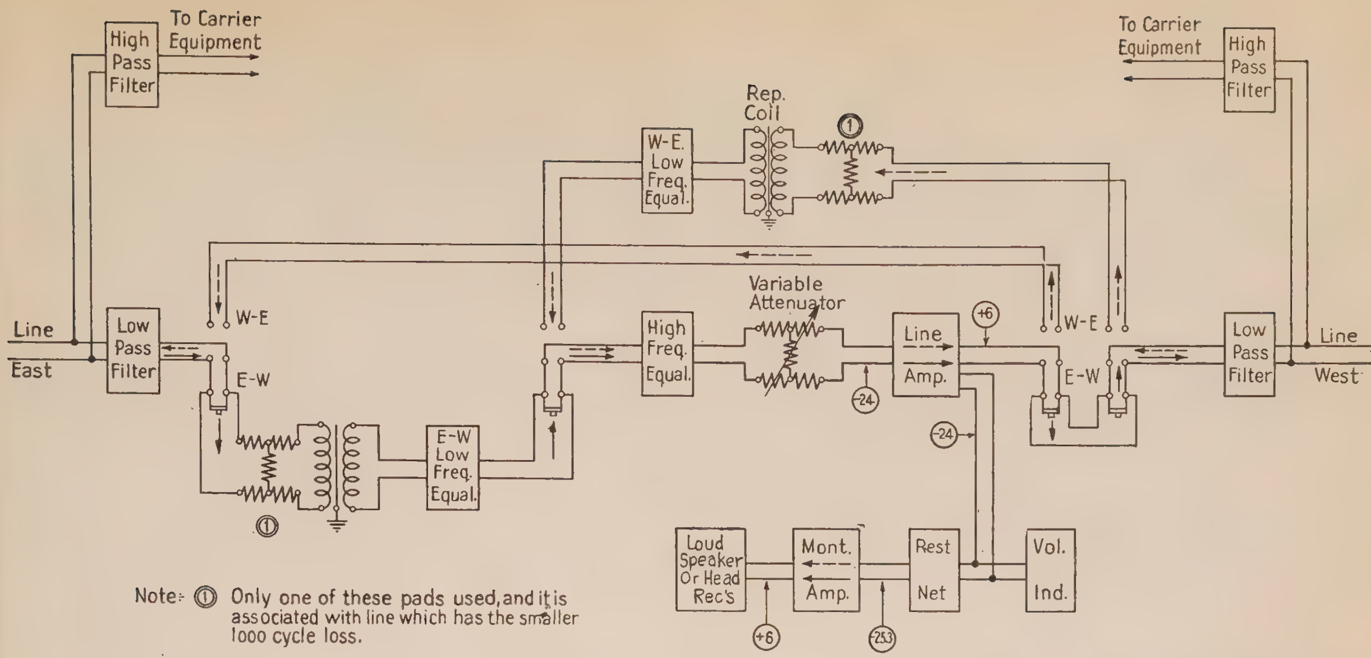


Fig. 15. Intermediate station layout



Note:- ① Only one of these pads used, and it is associated with line which has the smaller 1000 cycle loss.

Solid arrows show paths of East to West transmission.

Broken arrows show paths of West to East transmission.

Figures in circles indicate maximum volume at point shown.

Fig. 16. Intermediate station layout with different gauges

directs the program transmission to the program apparatus and the high pass filter, which has a low end cutoff around 9,000 cycles, directs the carrier transmission to its associated carrier equipment. Attenuation frequency characteristics of these filters are shown on Fig. 14. The low pass filter is of unusual design and is described at some length in a companion paper. (See "Line Filter for Program System," by A. W. Clement, p. 562–6 this issue.)

Monitoring Features

A very important factor in the satisfactory operation of a program system is the provision of monitoring arrangements by which the operating forces are enabled to observe the quality of transmission, listen for extraneous interferences, and observe indicating devices in order to make certain that the program is maintained at its proper volume.

Three types of aural monitoring facilities were provided on a trial basis for the new program system. The first type consists of a single unit loudspeaker operated by a suitable amplifier. With this loudspeaker system a good response characteristic from approximately 100 to 5,000 cycles is obtained, the low-frequency response depending, of course, upon the size of the baffle used with the loudspeaker.

The second type of monitoring consists of 2 headset receivers arranged with a proper equalizing network circuit. This type of monitoring provides good response characteristics from approximately 50 cycles to 8,000 cycles, enabling the observer to cover the entire program frequency range and thus permitting him to detect any extraneous interference which may be introduced even though this occurs at very low or very high frequencies.

The third type of monitoring consists of 2 loudspeakers and associated equalizing network with the loudspeakers mounted in a large baffle board. This arrangement affords a fairly uniform response from about 40 cycles to above 8,000 cycles. The particular type of monitoring which might be provided at the various stations would be governed by the service requirements involved.

To observe the volume on the program circuit, volume indicators are used. A new type of volume indicator was made available along with the new program system. This new device utilizes a full-wave copper oxide rectifier and has a much greater sensitivity range and materially improved indicating characteristics than the devices formerly used. The volume indicator is connected across the monitoring terminals of the line amplifier in which position it is bridged across a practically nonreactive 600-ohm impedance. Located thus it is also independent of line impedance affording more accurate results and obviating the necessity of correcting volume readings on account of line impedances. Also at this location it introduces no loss or phase distortion to the through program circuit.

The above constitutes a description of the major items employed in this program system. There are a number of other units, such as attenuators, repeating coils, etc., which will not be described in detail here but will be referred to as the need arises.

Typical Station Layouts

Due to the various requirements for different types of service and due in part to the different type of facilities, the general apparatus layouts and arrangements at different repeater stations are not always the same. Several of the more important general or typical layouts will be briefly discussed, however.

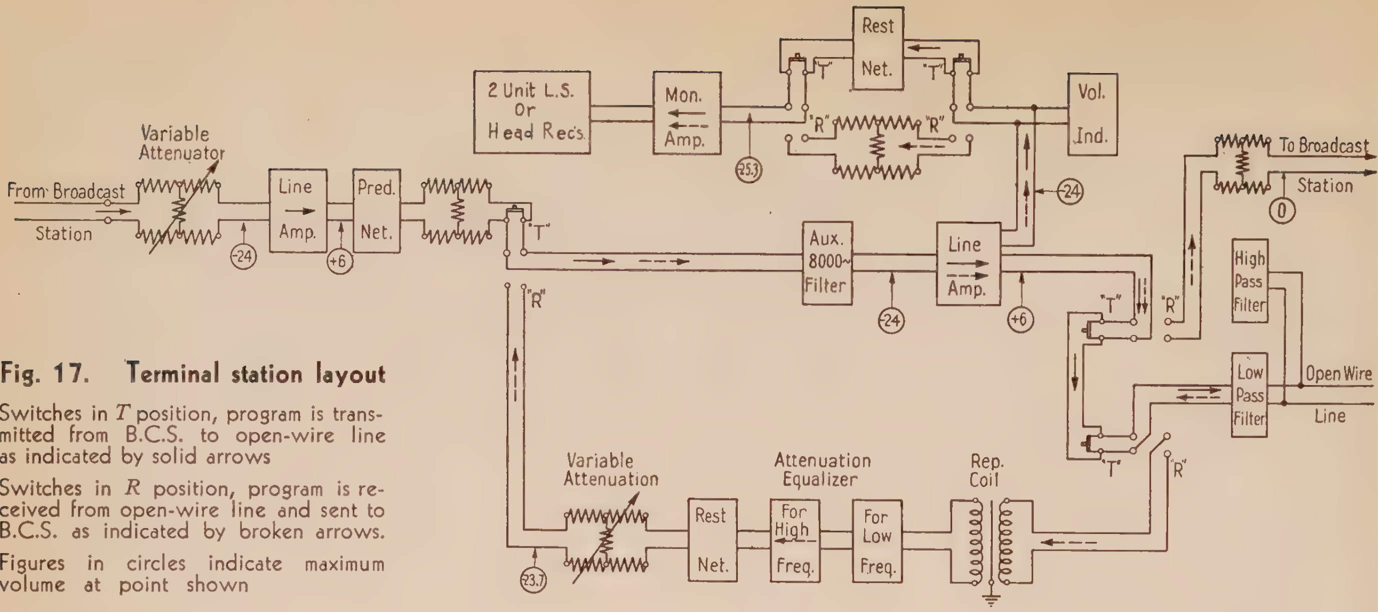


Fig. 17. Terminal station layout

Switches in *T* position, program is transmitted from B.C.S. to open-wire line as indicated by solid arrows

Switches in *R* position, program is received from open-wire line and sent to B.C.S. as indicated by broken arrows.

Figures in circles indicate maximum volume at point shown

On Fig. 15 is shown a layout of a typical intermediate station where bridging is not required and where the gauge of the wires in the 2 directions is the same. As may be noted from this figure, switching facilities are provided so that the apparatus may be connected into the circuit so as to properly take care of either the east-west or west-east transmission. For this type of layout most of the apparatus is common to both directions of transmission. The fixed artificial lines or pads indicated by Note 1 on Fig. 15 are for the purpose of building out whichever line has the lower 1,000-cycle attenuation so that this line and associated pad will have the same 1,000-cycle loss as the other line. As indicated, only one of these pads is required. This building out of the shorter line minimizes attenuator adjustment when the direction of transmission is reversed. The line amplifier in this as well as the other layouts to be discussed is always set for a gain of 30 db.

On Fig. 16 is shown the layout of a typical intermediate nonbridging station where the gauges of the wires on the 2 sides of the repeater station are different. As mentioned earlier each gauge of wire has its own particular low-frequency attenuation equalizer. Consequently, where the gauges of the wires on the 2 sides of the repeater station are not alike, it is necessary to arrange the station layout so that the proper low-frequency equalizer will be associated with the proper direction of transmission. This association of apparatus may be readily observed from Fig. 16.

On Fig. 17 is shown the layout of a typical terminal station. This layout differs from the intermediate station layout largely in the fact that provision must be made for the introduction of predistortion when the terminal station is transmitting a program to the open-wire line and in the provision of a restoring network when the terminal station is receiving a program from the open-wire line. The general layout of the apparatus may readily be observed by reference to the figure. The monitoring facilities at this type of station, in general, differ from those provided at the normal intermediate station in that a 2-unit loudspeaker is provided for use as desired.

On Fig. 18 is shown the layout of a typical intermediate bridging station where the gauge of the wires in the 2 directions is the same. This arrangement differs largely from the arrangement shown on Fig. 15 in that the bridging amplifier is inserted immediately ahead of the line amplifier so as to provide the necessary additional branches as required. The general circuit arrangements involved to take care of the different types of branches which may be encountered are indicated on this figure. The photograph, Fig. 19, shows the program equipment layout at an intermediate bridging station, which is of the type just discussed in Fig. 18, utilizing, however, only one branch circuit which is connected to a local broadcasting station.

In certain of the layouts just discussed, one apparatus unit designated as "aux filter" is shown which has not previously been mentioned. This is an 8,000-cycle low-pass filter somewhat similar to the low-pass line filter, except that it is not designed to operate in parallel with any high-pass filter. This filter is required at the transmitting and receiving terminals, in the branches feeding the radio station, and also in the high quality monitoring circuit to afford additional discrimination against unwanted high frequency interference as, for example, interference from the carrier channels. This arrangement of splitting the filter requirements enables a less expensive type of line filter set to be employed.

Over-All Performance

The initial application of this new program system was made on 2 transcontinental circuits between Chicago and San Francisco. One circuit, referred to as circuit 1, was routed through Omaha and Denver over the central transcontinental line. The other circuit, referred to as circuit 2, was routed via St. Louis and Kansas City to Denver and thence over the same pole lead as circuit 1. Circuit 1 was

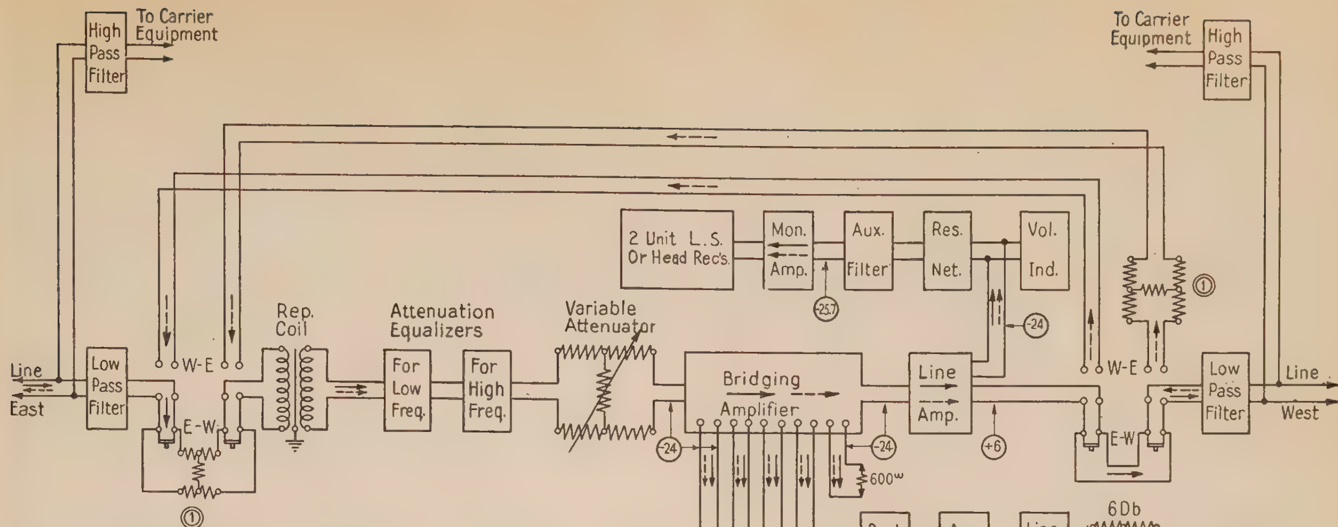
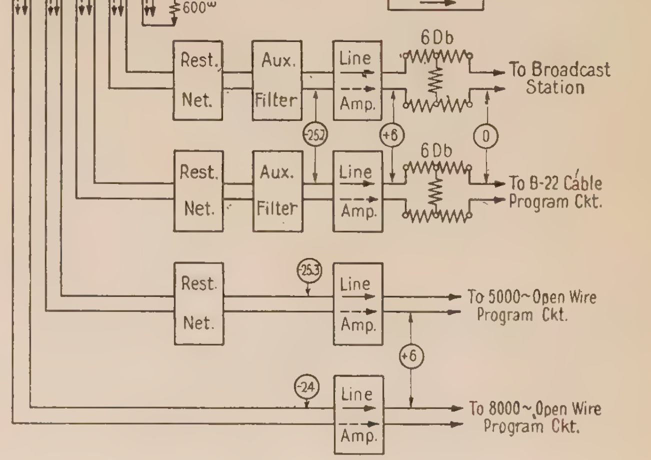



Fig. 18. Bridging station layout

approximately 2,395 miles long and was routed through 17 repeater stations involving 23 amplifiers in tandem. Circuit 2 was approximately 2,689 miles long and was routed through 19 repeater stations involving 29 amplifiers in tandem. Both circuits were routed through *B*-22 cable facilities between Sacramento and Oakland, Calif., and non-loaded cable facilities in the transbay submarine cable between Oakland and San Francisco.

At San Francisco a listening studio was set up in the Grant Avenue office where the program circuits terminated. A 2-unit loudspeaker with suitable connecting networks was set in a 7 x 7-ft baffle, the response of this loudspeaking system being practically uniform from about 40 cycles to above 8,000 cycles. The room in which the loudspeakers were located was acoustically treated so as to obtain the proper reverberation time. A powerful amplifier having a flat gain-frequency characteristic from 35 cycles to well above 8,000 cycles supplied the loudspeaker system. A high quality phonograph system for furnishing test programs was also installed at the Grant Avenue office. The records used were of the vertical cut type and included several recordings of a 75-piece orchestra as well as various solo and instrumental recordings. Two outside pickup points were used, one at the studios of one of the broadcasting companies at San Francisco and the other at a hotel. At both of these places the moving coil type of microphones was used and the latest type of high quality pickup amplifiers. The pickup system used at both these places had a response characteristic within about 2 db of being flat over the range of 35 to 10,000 cycles. At the Grant Avenue office, loud speaking equipment and considerable associated apparatus was installed for carrying out the various over-all tests.

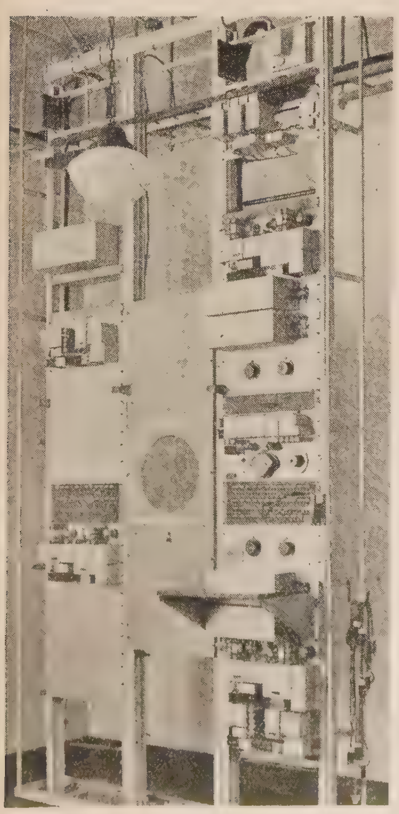


Fig. 19. Program equipment layout at an intermediate bridging station

Transmission and Other Measurements

In making transmission measurements, the circuit under test was first split up in a number of sections

and each section was then measured at 4 test frequencies, namely, 50, 100, 1,000, and 7,000 cycles. If the results were not within required limits the attenuators and equalizers were readjusted as required. The various sections were then connected together and the over-all circuit measured at several frequencies. In Fig. 20 is shown the transmission-frequency characteristics of circuit 1. The solid line is the average of 9 measurements while the dashed lines show the extreme deviations obtained for any of the 9 measurements. In Fig. 21 is shown corresponding data for circuit 2. For comparison purposes the average characteristics of the 2 circuits separately and the 2 of them connected in tandem making a loop circuit of over 5,000 miles are shown on Fig. 22.

Other measurements were made to determine whether nonlinear effects were produced. For example, 2 frequencies were applied to the circuit, one being measured and the other alternately cut off and on to determine whether one frequency adversely affected the transmission of the other or produced undesirable sum and difference products. Such distortion effects were found to be small. Measurements were made to determine whether the over-all transmission varied with the load applied. With a testing power which was varied in magnitude from 50 milliwatts to 0.1 milliwatt, the transmission varied slightly more than 1 db, that is, with the heavy load the circuit loss was somewhat more than 1 db greater than at the light load.

Noise and Crosstalk Survey

A noise and crosstalk survey was made on these program circuits and on message circuits on the same pole lead. Observations were made at the terminals of the message circuits while program was being transmitted on the program circuits to determine the amount of interference introduced into the message circuits from the program circuits, and, conversely, observations were made on the program circuits while various paralleling message circuits were in use, and the resulting interference was recorded.

The noise or crosstalk volume on the program circuits was measured by means of a volume indicator, which had inserted between it and the circuit at the point of measurement a network having a loss-frequency characteristic such that the various frequencies affecting the meter reading were attenuated or weighted in much the same way that the ear weights the different frequencies. Crosstalk volume and noise on the message circuit were measured with an indicating meter in much the same manner except that the network used here had an attenuation-frequency characteristic corresponding very nearly to that of the ear and an average telephone set. The network used on the program circuits was referred to as a "program weighting network," while that used with the message circuit was the ordinary "message weighting network." The noise and crosstalk volume was then recorded in decibels referred to reference noise with either program weighting or message weighting. Reference noise is that amount of interference which will produce the same meter reading as 10^{-12} watt of 1,000-cycle power, which is 90 db below 1 milliwatt.

The results of this survey indicated that in consideration of the layout and levels of the existing message circuits and of the noise existent on these circuits and on the program circuits, the value for maximum program volume, should, under normal conditions, be +3 referred to reference volume;

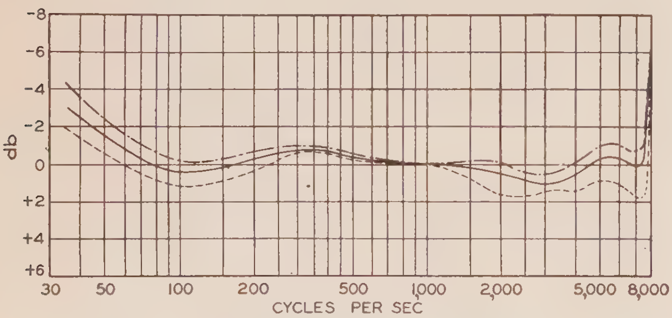


Fig. 20. Transmission-frequency characteristics of circuit 1, Chicago to San Francisco

Solid curves, average of 9 measurements
Dash curves, extreme deviations

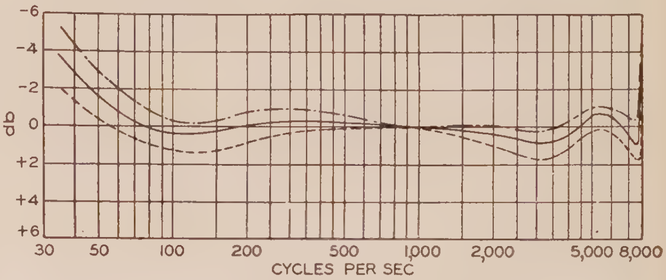


Fig. 21. Transmission-frequency characteristics of circuit 2, San Francisco to Chicago

Solid curve, average of 14 measurements
Dash curves, extreme deviations

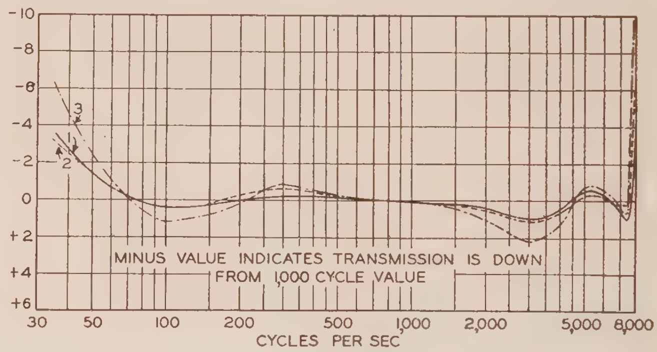


Fig. 22. Average characteristics of the 2 circuits separately and in tandem

Curve 1. San Francisco to Chicago on circuit 2, west to east
Curve 2. Chicago to San Francisco on circuit 1, east to west
Curve 3. San Francisco-Chicago-San Francisco loop (circuit 2, west to east, and circuit 1, east to west)
Circuit 2—2,689 miles, 29 amplifiers
Circuit 2—2,395 miles, 23 amplifiers
Loop—5,084 miles, 52 amplifiers

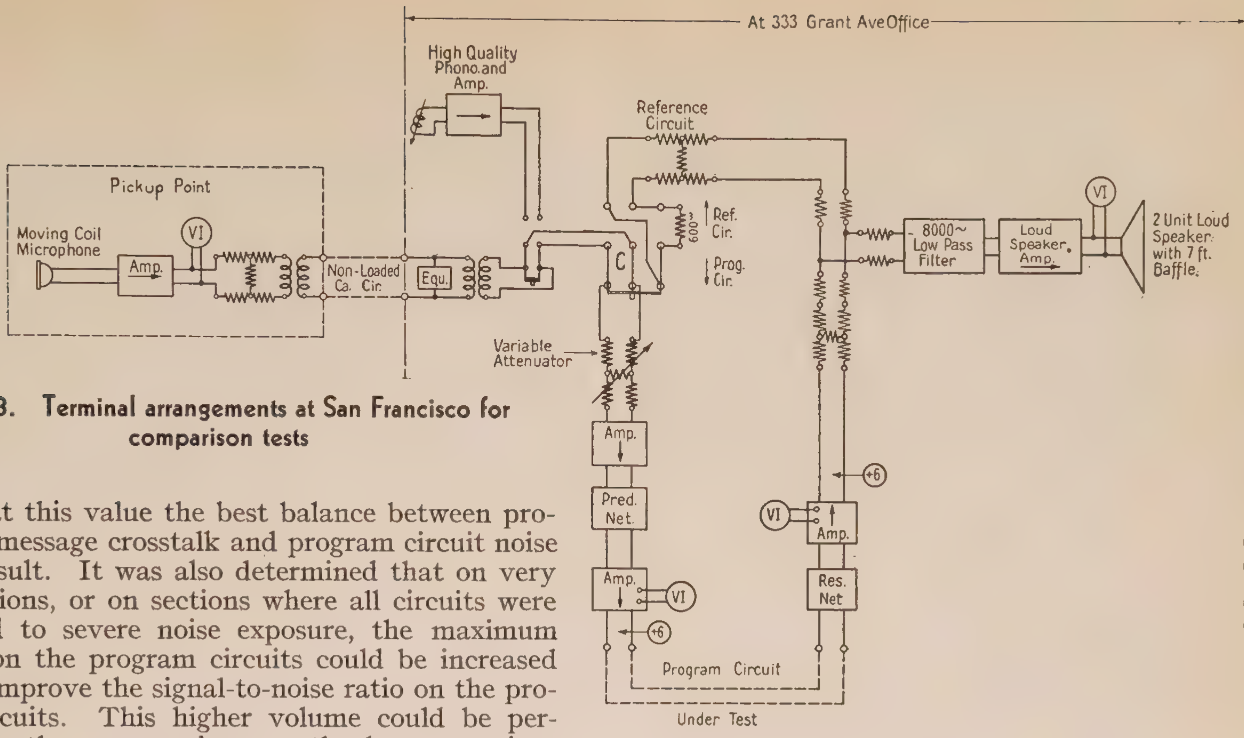


Fig. 23. Terminal arrangements at San Francisco for comparison tests

that is, at this value the best balance between program to message crosstalk and program circuit noise would result. It was also determined that on very long sections, or on sections where all circuits were subjected to severe noise exposure, the maximum volume on the program circuits could be increased 3 db to improve the signal-to-noise ratio on the program circuits. This higher volume could be permitted in these cases since on the longer sections the message circuits also usually operate at higher levels, and on the especially noisy short sections the increased crosstalk to the message circuits will ordinarily be masked by the greater noise.

The average noise measured at San Francisco or Chicago at the circuit terminals at the reference volume point was 49 db above reference noise "program weighting" when the restoring network was included at the receiving terminal. The noise averaged 5 db higher than this with the restoring network removed. This value of noise is about 43 db below the maximum power of the program measured at the same point with the same measuring instrument. This, therefore, establishes a signal-to-noise ratio of about 43 db, thus permitting a volume range of approximately 40 db.

Critical Listening Tests

The various tests referred to gave statistical data concerning the transmission performance of the circuits from which it could readily be predicted that the circuits would transmit programs with very little impairment to quality. To substantiate this, very critical listening tests were made comparing the quality of a program after it had been transmitted over various length circuits with the same program transmitted over a reference circuit which was distortionless over the frequency range for which the circuits were designed, namely, to 8,000 cycles. In Fig. 23 is shown schematically the terminal arrangements employed at San Francisco for these listening, or, as they are more commonly called, comparison tests.

Various types of programs were used, such as speech, vocal and instrumental selections, and orchestral renditions, both classical and jazz. Quite a number of observers were used, some of whom were present on several tests and a few on all tests. On tests made on a San Francisco-Denver-San Francisco loop involving 2,600 miles of circuit, no observer was able to consistently differentiate between the quality over the reference circuit and that over the program circuit. On tests made on the San Francisco-Chicago-San Francisco loop certain of the more experienced observers were able to differentiate between the circuits somewhat more than 50 per cent of the time, but this, it must be remembered, was on a direct comparison test. None of the observers could tell with any assurance which was the program circuit and which was the reference circuit if a few minutes were allowed to elapse between switches. On the Chicago loop 264 observations were made on direct comparison tests on which 60 per cent of the observations favored the reference circuit and 40 per cent favored the program circuit.

Other Tests of Over-All Performance

Included as part of the over-all program, were tests to determine the volume range, maximum volume obtainable, and speed with which the circuits could be reversed.

On the volume range tests a source of program was obtained and so regulated that it had a very narrow volume range. This was then applied to the circuit with the sending end gain adjusted so that the maximum volume applied at the repeater outputs was +6. The sending end gain was then gradually decreased so as to apply a gradually decreasing volume to the circuit. This process was continued until the program volume was so weak that the line noise interfered with its satisfactory reception. The amount that the sending end gain was adjusted determined the volume range. The average value for several tests was slightly in excess of 40 db. The maximum volume was determined by switching a 10-db pad from the sending end to the receiving

end of the circuit and listening to a transmitted program, noting the point at which there was a quality difference between the high volume and low volume condition. It was found that a slight difference could be detected when the maximum volume on the high volume condition was +10, thus showing the circuit was capable of handling a maximum volume slightly lower than this value.

As mentioned earlier, switching means are provided at each station for reversing the direction of transmission. On the initial field tests it was demonstrated that the circuits could be reversed readily and at the same time maintain satisfactory over-all characteristics. At the present time, on receipt of proper advance notice, the circuits are being reversed on commercial programs in approximately 30 secs.

Conclusion

The above development provides a program transmission system applicable to open-wire lines which even for very long distances will provide transmission characteristics which should be adequate for program transmission for a number of years to come.

The author makes grateful acknowledgment to the National Broadcasting Company and the Columbia Broadcasting System for their assistance in making available the program pickup sources at San Francisco.

Line Filter for Program System

Open wire circuits recently have been developed for transmitting radio broadcast programs with greater naturalness and over greater distances than heretofore (see companion paper "Wide-Band Open-Wire Program System" in this issue). The simultaneous utilization of these circuits for the transmission of broadcast programs and carrier telephone messages requires the use of line filters to restrict the program and carrier currents to the proper circuits. The low pass line filter developed for the program circuits and its contribution to the maintenance of good quality in the programs transmitted are described in this paper.

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PROGRAM transmission systems operated on open wire telephone lines ordinarily are not assigned the exclusive use of the lines, but usually share them with other communication facilities. The wide band system described in an accompanying paper[1] transmits currents in the frequency band extending from 35 to 8,000 cycles per second, while the lines over which it is routed possess useful transmission ranges extending from 35 to considerably above 30,000 cycles. In order that the range above 8,000 cycles shall not be wasted, carrier telephone systems utilizing these frequencies usually are operated on the same wires with the program systems.

Line filters are used at each terminal and repeater point in the program system to separate the program currents from the carrier currents and to guide each to the proper channel. They are operated in sets consisting of a low pass filter and a high pass filter connected in parallel at one end, the end that faces the line. The low pass filter transmits the program currents freely while effectively excluding the carrier currents, and the high pass filter transmits the carrier currents while excluding the program currents.[2]

The line filters are located in the open wire program systems as shown in Figs. 1, 15, 16, 17, 18, and 20 of the accompanying paper by H. S. Hamilton.[1] The low pass filter is in the direct path of the program currents and therefore has a number of features of special interest. It is the object of this paper to describe this filter and its contribution to the maintenance of good quality in the programs transmitted over the system.

This low pass line filter, with its associated high pass filter, makes it possible to use the open wire lines simultaneously for wide band program service and for commercial carrier telephone service, without impairing the quality of the program. It represents an improvement over older types of line filters, as well as an advance in the technique of equalization in filters. In cases requiring careful delay and loss equalization, it has been the usual practice to design the filter first to supply the required discrimination or filtering action, and then design a delay corrector

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1. For all numbered references see list at end of paper.

to correct for the delay distortion in the filter, after which a loss equalizer is designed to correct for the amplitude distortion in both the filter and the delay corrector. The loss equalizer introduces a small delay distortion which usually can be anticipated and corrected in the delay corrector. In the wide band program filter the functions usually performed by these 3 separate types of networks have been combined, with a consequent saving in cost and space.

Requirements to Be Met by Program Filter

To function effectively as a line filter, the low pass filter must provide sufficient discrimination against carrier currents to make their effect completely inaudible in all the receivers connected to the program system. Discrimination varying from 46 to about 90 db is necessary to accomplish this end. Because of the presence of an auxiliary low pass filter[1] which supplies considerable loss in the frequency ranges where the requirement is unusually severe, each line filter need furnish discrimination varying only from 40 to about 60 db.

From the standpoint of program quality, it is essential that the line filter, while furnishing the foregoing discrimination, shall not introduce any appreciable distortion into the program. This requirement would call for nothing unusual in the way of filter design if there were only a few filters in the system. Long open wire program systems, however, may extend as far as 3,000 or 4,000 miles, and may contain as many as 50 low pass line filters. A program that has traversed such a circuit still must be comparable in quality to a program that is broadcast from the point at which it originated. Since the system contains much other apparatus, such as equalizers and amplifiers, each low pass line filter can be permitted to introduce not more than about 1/100 of the distortion that can be tolerated in the whole system, assuming 50 filters in the system.

There are 2 types of distortion that must be controlled very carefully in the program filter: these are (1) amplitude distortion, and (2) delay, or phase, distortion. Amplitude distortion is introduced by a filter when its loss is not the same at all frequencies in the transmitted band, currents of

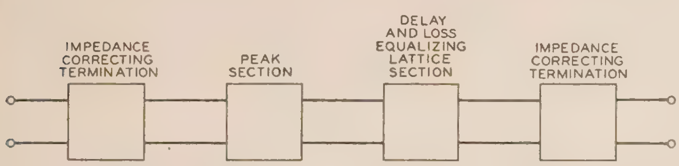

Fig. 1. Block schematic diagram of filter

some frequencies being attenuated more than others. The effect of amplitude distortion on the program is to change the relative intensities, or volumes, of tones of the frequencies at which distortion occurs, thus impairing the naturalness of the program. Amplitude distortion ordinarily can be corrected without much difficulty by means of suitable attenuation equalizers.

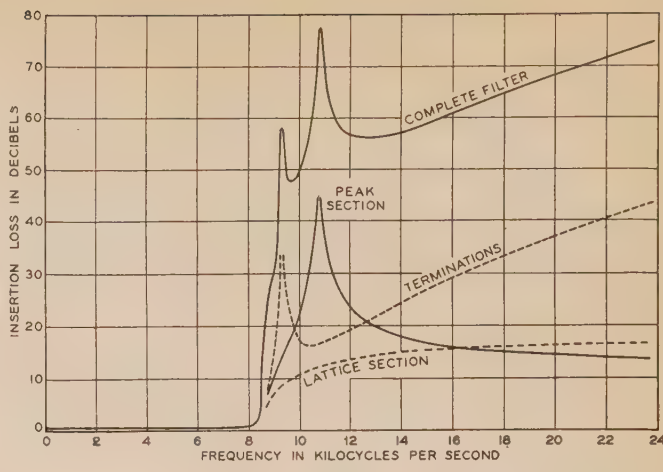

Fig. 2. Loss in filter and in component sections

Delay distortion is introduced by a filter when different frequency components of a signal require different lengths of time for propagation through the filter. This type of distortion is related directly to the shape of the phase shift-frequency characteristic. The slope of this phase shift curve usually is taken as a measure of the delay introduced by the filter. Stated mathematically, the delay in seconds is taken as $\frac{\partial B}{\partial \omega}$, where B is the phase shift in radians and ω is $2\pi f$, f being the frequency in cycles per second. Thus if the phase shift of the filter is proportional to frequency, $\frac{\partial B}{\partial \omega}$, or the delay, is constant and there is no delay distortion. In this case the wave form of a signal transmitted through the filter remains unchanged, the signal being delayed in transmission an interval of time corresponding to the slope of the phase shift curve. If the slope of this curve is not constant over the transmitting band of the filter, however, delay distortion is introduced. In low pass filters, the difference between the slope of the phase shift curve at a given frequency and the minimum slope of the curve is a measure of the delay distortion at that frequency.

A discussion of delay distortion in telephone apparatus, including filters, as well as a discussion of the effect of delay distortion on telephone quality, may be found in 2 recent articles on these subjects.[3,4] Whereas the effect of amplitude distortion is to weaken or strengthen some of the tones in the sound being transmitted with respect to the other component tones, the effect of delay distortion is to introduce unnatural audible effects which may become so pronounced as to be annoying if the delay distortion be great enough.

Delay distortion is present in most filters used in communication work, but ordinarily not in such magnitude that its effect is noticeable. As a rule, it need be considered only when a large number of filters is used in a single circuit, as in the case of the program systems. Delay distortion is in general more difficult to correct than amplitude distortion. One of the unusual features of the low pass line filter used in the wide band program circuits is

the means employed to keep it free from delay distortion.

The filter consists of 4 parts, each with distinguishing functional characteristics. The separate parts, or sections, have image impedances such that when they are joined together no current is reflected at the junctions. Figure 1 shows the filter in block schematic form. Each part of the filter provides some of the attenuation required to exclude carrier currents from the program circuit, the attenuation of the complete filter being the sum of the attenuations of all parts. On Fig. 2 are shown the loss-frequency characteristics of the various sections and of the complete filter.

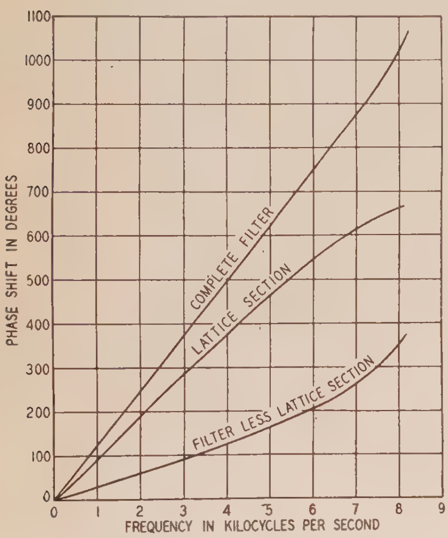

Fig. 3. Phase shift in filter and in component parts

Delay Equalization

Likewise, the phase shift of the complete filter is the algebraic sum of the phase shifts of all sections. The phase shift of the filter exclusive of the delay and loss equalizing section is similar to that of the usual ladder type low pass filter. Over the lower frequencies of the transmitting band the phase shift-frequency characteristic is practically linear with frequency, but at the higher frequencies the slope of this curve increases gradually with frequency and becomes very large near the upper edge of the band. Phase shift varying in this manner introduces much more delay distortion than can be tolerated, and therefore has to be corrected. It is one of the functions of the delay and loss equalizing section, which is of the lattice type, to correct for this distortion. The phase shift of this lattice section is such that when it is added to that of the rest of the filter the total phase shift is very nearly proportional to frequency over the whole program band, and delay distortion thus is almost entirely eliminated.

The property of the lattice section by which its phase shift can be made to vary with frequency in the desired manner is expressed in the following characteristic equation, which holds only in the transmitting band and when the section is terminated in its image impedances[5]:

$$\tan\frac{B}{2} = \frac{Kf\left(1-\frac{f^2}{f_2^2}\right)\sqrt{1-\frac{f^2}{f_c^2}}}{\left(1-\frac{f^2}{f_1^2}\right)\left(1-\frac{f^2}{f_3^2}\right)} \qquad (1)$$

In this equation, B is the phase shift in radians; f is the frequency in cycles per second; f_1, f_2, f_3, and f_c are frequencies at which the phase shift of the section is successive multiples of π radians or 180 deg, f_c being also the cut-off frequency of the filter; and K is a constant controllable by assigning the proper values to the coils and condensers of the section. By assigning to f_1, f_2, and f_3 the values of frequency at which it is desired that the phase shift of the section shall be π, 2π, and 3π radians, respectively, and by giving K the proper value, the phase shift-frequency curve is made to approximate the ideal one which completely would correct the delay distortion of the filter. Figure 3 illustrates the building up of the phase shift characteristic.

The delay corresponding to the rate of change of the phase shift with frequency is plotted in Fig. 4. The average delay introduced by the filter is about 0.00033 sec. It may be noted that for frequencies below 7,500 cycles per second, the variation from this average does not exceed 0.000025 sec. Thus the delay due to 50 filters in a long program circuit does not deviate from the average in this frequency range by more than 0.00125 sec. Distortion of this amount ordinarily would not be detected by the average listener. Above 7,500 cycles per second the delay gradually increases with frequency, rising quite rapidly outside the program band. The high attenuation at frequencies above the program range, however, eliminates any effect this distortion otherwise might have on the program.

Loss Equalization

Another function of the lattice section is to make the loss of the filter constant in the program frequency band. In a dissipationless filter terminated in its image impedances (which is substantially the condition under which this filter is operated) the loss in the transmitting band is zero. The effect of dissipation is to introduce a loss which is given approximately in this band by the equation:

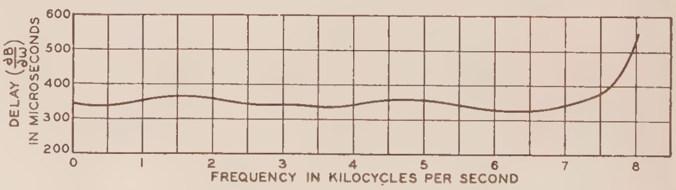

Fig. 4. Delay-frequency characteristic of filter

The ordinates of this curve are proportional to the slope of the upper curve of Fig. 3

$$A_d = \frac{\omega}{2Q}\frac{\partial B}{\partial \omega} \qquad (2)$$

where A_d is the loss due to dissipation, B is the phase shift of the nondissipative filter, and Q is the average dissipation factor of the coils (dissipation in the condensers being negligible, ordinarily). The factor Q

is equal to the average of the ratios $\frac{\omega L_e}{R_e}$, and $\frac{\omega}{2Q}$ in eq 2 therefore may be written $\frac{R_e}{2L_e}$, where R_e and L_e are the effective resistance and effective inductance, respectively, of the coils.

In the coils of the program filter, Q is about proportional to frequency over the lower portion of the program band, but above this range the factor $\frac{\omega}{2Q}$ increases with frequency. For the filter exclusive of the lattice section, the factor $\frac{\partial B}{\partial \omega}$ is also greatest at the higher frequencies, as may be seen from the lower curve in Fig. 3; hence this part of the filter introduces much more amplitude distortion than is permissible. For the lattice section alone, however, the factor $\frac{\partial B}{\partial \omega}$ is greatest at the lower frequencies, as is apparent from the middle curve of Fig. 3. Thus the natural tendency of dissipation in the lattice section is to compensate for the distortion in the other sections of the filter. This compensating tendency can be controlled to a considerable degree, since by eq 2 A_d is proportional to R_e. By proper adjustment of the effective resistance of the coils of the lattice section, its loss is made practically complementary to that of the rest of the filter, so that the loss of the complete filter is substantially constant throughout the program range.

The loss of the filter in the transmitting frequency band is shown in Fig. 5. The average loss below 7,000 cycles per second is about 0.53 db and the deviation from this average does not exceed 0.03 db. Considering again a circuit containing 50 filters, the deviation from the average loss introduced by the filters does not exceed 1.5 db in this range. Between 7,000 and 7,500 cycles per second the amplitude distortion per filter is about 0.10 db, and above 7,500 cycles the loss increases in such a way as to tend to mask the small delay distortion in this range.

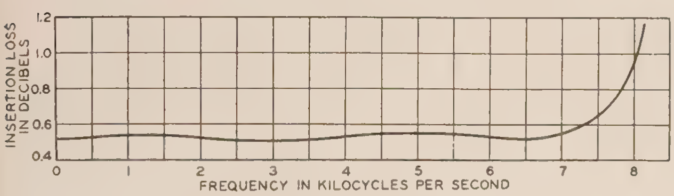

Fig. 5. Loss of filter in program frequency band

Impedance Correction

In the discussion of the lattice section it was stated that its phase shift is given by eq 1 only when the section is terminated in its image impedance. To facilitate the design and simplify the filter structure, this section has been given an image impedance of the simplest type. This impedance, Z_I, varies with frequency according to the following equation:

$$Z_I = \frac{Z_o}{\sqrt{1 - \frac{f^2}{f_c^2}}} \tag{3}$$

where Z_o is the "nominal impedance" of the filter, a constant equal approximately to the average impedance of the open wire lines in the program band; and f_c is the theoretical cut-off frequency. Thus the image impedance rises with increasing frequency to a very high value near the cut-off; and, since the line impedance is practically constant except at very low frequencies, a large mismatch would result at the upper edge of the transmitted band if the lattice section were connected directly to the line. The impedance correcting sections at the ends of the filter are employed to avoid this mismatch. The properties of these sections are such that when they are inserted between the lattice section and the line or the office terminating apparatus, the impedance of the filter matches that of the line and the office apparatus, and the lattice section faces its own image impedance. In this manner, both internal and external reflections largely are avoided; and the phase shift of the lattice section has the proper value.[6]

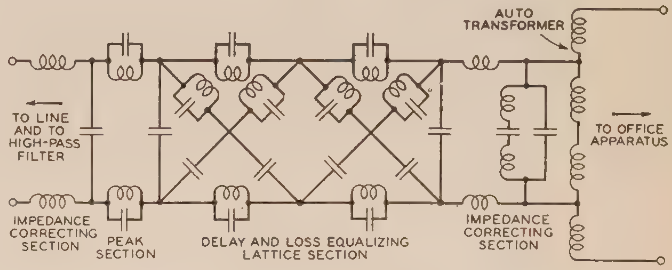

Fig. 6. Schematic diagram of filter

The general theory on which the design of the impedance correcting sections is based is discussed at length in a recently published article.[7] In brief, the sections consist of 2 parts: a 4-terminal network to make the resistance of the filter approximately constant over the program band, and a 2-terminal network placed in shunt at the end to cancel the reactance of the filter in this band. The inductance and capacitance of the coils and condensers of the 4-terminal network are related to the coefficients of a power series expansion of the right-hand part of eq 3 in the manner explained in the article by H. W. Bode.[7] The 2-terminal shunt network at the apparatus end is designed so that, while canceling the reactance of the filter in the program band, it resonates just above the band to produce a peak or sharp maximum of attenuation. It thus supplies the sharp selectivity required to produce an abrupt change from free transmission of the program frequencies to high attenuation of the carrier frequencies.

At the line end, the impedance correcting section is designed for parallel connection with the high pass

line filter. The high pass filter itself acts as the shunt reactance-canceling network.

The peak section shown at the left of the delay and loss equalizing section in Fig. 1 provides attenuation which rises rapidly with frequency above the program band in such a way as to add to the selectivity of the filter. It is a ladder section of a type often employed in filters for its selectivity.

The filter is designed to match the average impedance of the open wire lines. The impedance of the office apparatus, however, is slightly higher than that of the lines and the filter. An autotransformer therefore is used at the end of the filter connected to the office apparatus, to effect the required change in impedance. A schematic diagram of the complete filter is shown on Fig. 6, the parts being marked for identification in accordance with the foregoing discussion.

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A Graphical Solution of Steady State Stability

The steady state stability limit of a power system, and adjusted synchronous reactance, are considered in this paper. A graphical solution of the problems of the determination of the steady state power limits is described, based directly upon the use of the general circuit constants of the transmission line.

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IT IS often desirable to determine the steady-state power limit of a system which, for simplicity, is represented by a generator, a transmission line, and a synchronous motor. The 2 synchronous machines may be represented each by a number of ohms of synchronous impedance and in the problem to be considered here, the voltages at the terminals of the machines are given.

A graphical solution is convenient for this problem, and has been presented in the paper "Steady State Stability in Transmission Systems" by Edith Clarke (A.I.E.E. Trans., v. 45, 1926, p. 24, Fig. 3) where the transmission line of the problem is represented by its equivalent π line. (See also the discussion by C. F. Wagner on p. 90 of the same volume.)

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery and scheduled for discussion at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934. Manuscript submitted Jan. 15, 1934; released for publication March 13, 1934. *Not published in pamphlet form.*

In the present paper, a graphical solution is described for the above problem, in which the general circuit constants of the long transmission line are used, instead of the equivalent π line.

Let Z_1 and Z_2 be the synchronous impedances of the generator and the synchronous motor indicated in Fig. 1 and let A, B, C, and D be the general constants of the complete system shown in Fig. 1.

$$\text{Then } E_2 = DE_1 - BI_1 \tag{1}$$

$$\text{and } I_2 = -CE_1 + AI_1 \tag{2}$$

where the voltages are from line to neutral.

These equations constitute definitions of the 4 general constants.

A description of the use of these general constants may be found in "The Calculation of Transmission Line Networks" by T. R. Rosebrugh, Engineering Research Bulletin, University of Toronto, 1919; in Part II of the paper "Power Limitations of Transmission Systems" by R. D. Evans and H. K. Sels, A.I.E.E. Trans., v. 43, 1924, p. 33–8; or in "Electric Circuits," Chap. IX, by O. G. C. Dahl. An alternative method of finding these constants was described by the author in "Electrical Characteristics of Transmission Systems," A.I.E.E. Trans., v. 41, 1922, p. 781–4.

From a point O on cross section paper plot the complex quantity Z_2A ohms, thus locating the point R, Fig. 2. From O also plot B ohms, locating the point P and then plot $B - \dfrac{Z_1}{A - CZ_1}$ ohms, locating the point S.

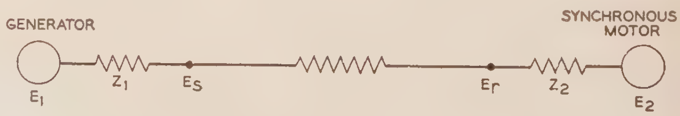

Fig. 1. Representation of power system

If $A = a_1 + ja_2$
and $B = b_1 + jb_2$

find an angle ϕ such that

$$\tan \phi = \frac{a_1b_2 - a_2b_1}{a_1b_1 + a_2b_2} \tag{3}$$

If polar expressions are used, such that

$A = |A| \underline{/\lambda}$
and $B = |B| \underline{/\mu}$
then $\phi = \mu - \lambda$ (4)

Draw MC, Fig. 2, perpendicular to OP at its middle point M, and on the side shown. Make $MC = MP/\tan \phi$. With C as center describe

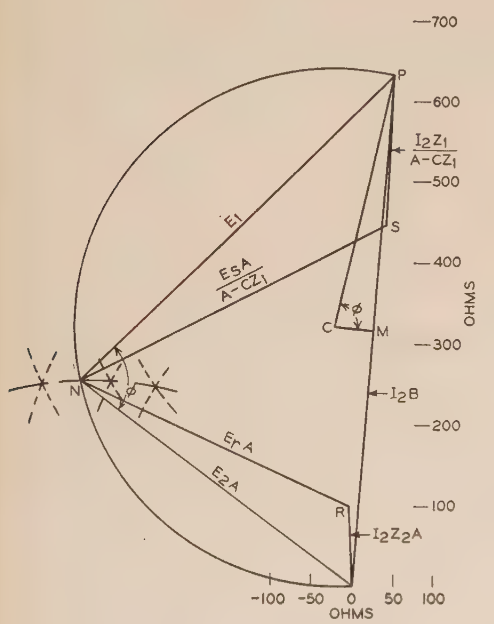

Fig. 2. Diagram for graphical solution

a circle passing through the points O and P. Any pair of lines drawn from O and P to a point on this circle will meet at an angle ϕ, which is a desired characteristic.

Now choose 2 arbitrary lengths which have the ratio of $|E_rA|$ to $|E_sA/(A - CZ_1)|$. On the left-hand side of OP draw an arc with center R and radius equal to the first of the above lengths and draw an arc to cut it, with center S and radius equal to the other length. Repeat this with 2 or more pairs of radii of the same ratio and draw a curve through the intersections of each pair of arcs. Let this curve cut the circle in N and draw lines from N to O, R, S, and P. These lines are proportional to voltages.

Measure NR. Its length is proportional to the known voltage $|E_rA|$, and this gives the voltage scale. From NP find E_1, using this scale, and from NO find $|E_2A|$ from which E_2 may be found.

The maximum power output of the synchronous motor is given by the well-known result,

$$\frac{3}{1{,}000}\left[\left|\frac{E_1E_2}{B}\right| - \left|\frac{E_2^2}{B^2}\right|(a_1b_1 + a_2b_2)\right] \text{kw} \tag{5}$$

or

$$\frac{3}{1{,}000}\left[\left|\frac{E_1E_2}{B}\right| - \left|\frac{E_2^2A}{B}\right|\cos(\mu - \lambda)\right] \text{kw} \tag{6}$$

The value of the current I_2 may be found from the fact that I_2B volts is equal to OP, Fig. 2, using the voltage scale previously found. Dividing by B gives I_2 from which the losses in the synchronous motor may be found, if desired. The phase angle of I_2 is a horizontal line in Fig. 2, since I_2 times resistance is a horizontal line in that diagram.

After the armature and field currents of the synchronous machines have been found, the values of synchronous reactance should be changed to correspond and the problem should be repeated, thus obtaining the "adjusted synchronous reactance." (See Appendix A.)

In deriving the expressions which have been used in this problem,

$$E_1 = E_2A + I_2B \tag{7}$$

from which OP is plotted.

$$E_rA = E_2A + I_2Z_2A \tag{8}$$

from which OR is plotted.

$$E_1 = E_s + I_1Z_1 \tag{9}$$

and directly from eq 2,

$$I_1 = \frac{CE_1}{A} + \frac{I_2}{A}$$

$$\text{then } I_1 = \frac{CE_s}{A} + \frac{CI_1Z_1}{A} + \frac{I_2}{A}$$

$$I_1Z_1(A - CZ_1) = CE_sZ_1 + I_2Z_1 \tag{10}$$

$$\text{From eqs 9 and 10, } E_1 = E_s\left(\frac{A}{A - CZ_1}\right) + \frac{I_2Z_1}{A - CZ_1} \tag{11}$$

from which PS is plotted.

The voltages OR, OP, and PS all involve I_2 which at first is unknown, but the coefficients in ohms can be plotted, as already described.

Example (See Fig. 2.)

Let $A = 0.620 + j\,0.043$
$B = 50 + j\,630$
$C = -0.000021 + j\,0.00152$
$Z_1 = Z_2 = 4 + j\,160$
$E_r = E_s = 86{,}600$ volts to neutral

Then $Z_2A = OR = -4 + j\,99$
$B - Z_1/(A - CZ_1) = 37 + j\,445$
$\tan \phi = 6.70$
$|E_rA| = 53{,}800$
$|E_sA/(A - CZ_1)| = 62{,}200$

From Fig. 2,
$E_1 = 80{,}000$, $E_2 = 100{,}000$

and maximum power $= 33{,}000$ kw.

Appendix A—Adjusted Synchronous Reactance

In the calculations described in this paper, as well as in many other calculations, the number of ohms to be taken for the synchronous reactance of a machine is of importance. It should be such as to make the vector diagram of the machine of as nearly as possible the same proportions as the vector diagram drawn by more elaborate methods such as that involving the armature ampere-turns.

One value of synchronous reactance for a machine will not suit all load conditions, but different values are required for different load currents and for different field currents. Values of synchronous reactance obtained from zero power factor tests at strong field current, corresponding to generator load of lagging power factor, are found to be applicable, to a reasonable degree of accuracy, at loads of other power factors, when the machine is not under-excited, pro

vided the armature and field currents are the same as those at which the zero power factor measurement was made.

Maximum Power With Given Field Currents

Let a synchronous motor with fixed field current giving excitation voltage E_m to neutral be supplied with current from a generator with fixed field current giving excitation voltage E_g. Let Z be the total impedance made up of the adjusted synchronous impedance of the generator and motor and the impedance of the circuit between them. Let letters without dots represent absolute values and let $\dot{Z} = Z(\cos\gamma + j\sin\gamma) = Z\,\underline{/\gamma}$. Let E_m be reference vector and $\dot{E}_g = E_g\,\underline{/\alpha}$. Then, $\dot{I} = \dfrac{\dot{E}_g - E_m}{\dot{Z}} = \dfrac{E_g\underline{/\alpha} - E_m}{Z\underline{/\gamma}}$

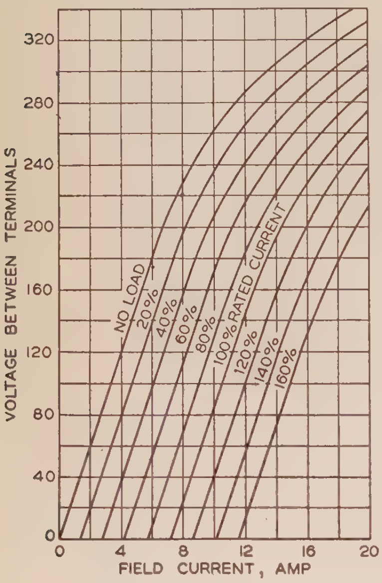

Fig. 3. Zero power factor curves of a 44-kva machine

According to well-known equations, the power which is the sum of the mechanical load on the motor and its losses except resistance loss, is equal to the real part of 3 $E_m\dot{I}$ and is

$$P_{\text{motor}} = \frac{3E_gE_m}{Z}\cos(\alpha - \gamma) - \frac{3E_m^2}{Z}\cos\gamma \quad \text{watts} \quad (12)$$

The maximum value of this power is when $\alpha = \gamma$ and is

$$P_{\max} = \frac{3E_gE_m}{Z} - \frac{3E_m^2R}{Z^2} \quad \text{watts} \quad (13)$$

The current at pull-out is

$$I = \frac{1}{Z}\sqrt{(E_g^2 + E_m^2 - 2\,E_mE_gR/Z)} \quad (14)$$

If the resistance is negligible,

$$P_{\max} = 3\,E_gE_m/X \text{ watts} \quad (15)$$

$$\text{and } I = \frac{1}{X}\sqrt{(E_g^2 + E_m^2)} \text{ at pull-out} \quad (16)$$

where the voltages are from terminal to neutral. (See "Adjusted Synchronous Reactance and Its Relation to Stability," by H. B. Dwight, *Gen. Elec. Rev.*, v. 35, 1932, p. 609–14.)

In calculating maximum power, a successive approximation must be made. A value of armature current is chosen and the synchronous reactance for that current and for the specified field current is taken from the zero power factor saturation curves, such as Fig. 3. The current for the maximum power condition is then computed, and if it is appreciably different from the value originally assumed, the calculation should be repeated with a better assumed value.

Example. (From thesis of W. J. O'Neill at Massachusetts Institute of Technology.)

Find the maximum power for 2 machines separated by 0.41 ohms reactance.

Generator, 44 kva, 230 volt, 110 amp, 1,200 rpm, 11.6 amp field current
Saturation curves, Fig. 3
Motor, 36 kva, 230 volt, 90 amp, 1200 rpm, 4.2 amp field current

After 2 or 3 trials, using eq 14, the current at pull-out was computed to be 107 amp.

This is 97 per cent of 110 amp, the rated generator current. From Fig. 3, for 11.6 amp field current, the generator synchronous reactance is:

$$X_g = \frac{281 - 134}{107\sqrt{3}} = 0.79 \text{ ohms}$$

A similar calculation for the motor gave 0.84 ohms and 248 volts excitation voltage between terminals.

$$X = 0.79 + 0.41 + 0.84 = 2.04 \text{ ohms}$$

$$P_{\max} = \frac{3 \times 281 \times 248}{3 \times 2.04} = 34.1 \text{ kw}$$

The maximum power by test was 35.1 kw, the discrepancy being about 3 per cent.

For other examples of this method, see the paper, previously referred to, by the author in the *General Electric Review*, v. 35, 1932, p. 609–14.

A Vacuum Tube Controlled Rectifier

An electronic rectifier built for testing radio transmitting tubes is described, and some of the factors influencing precision of control are discussed briefly.

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THE PURPOSE of this paper is to discuss a vacuum tube controlled rectifier, developed and built for testing experimental and semiproduction radio transmitting tubes. The set required had to supply filtered direct current at any voltage from 50 to 5,000 volts; had to hold voltage at any set point within 1 per cent, regardless of supply voltage fluctuations up to 15 per cent and load current variations up to 2 amperes full load; had to have a feature capable of limiting the current output to any value from 1 ampere up, even on short circuit, without affecting the voltage regulation up to the current limit; the operation of the set was to be as simple as possible; it was to have a high order of reliability

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and be constantly available; and finally the completed unit was to fit into an existing space $4^1/_2$ by $2^1/_2$ by 3 ft. These severe specifications were completely met by a hot cathode mercury vapor rectifier set of conventional design, the primary voltage of which is controlled by saturable reactors with vacuum tube control. The system involved is unusual, and is capable of a wide variety of applications and high precision of control. The set built for this specific problem will be described, and the factors influencing precision of control by the system used will be discussed briefly.

The Rectifier Built

Reduced to its essentials, the set developed consisted of the components shown in Fig. 1. The main unit is a 10-kw full wave hot cathode rectifier, rated 220-volt 3-phase input, 6,000 volts d-c output. In the a-c input to the set are 3 reactors with d-c saturating windings. By means of these saturating windings, the impedance of the reactors may be varied, from a very high value (when no direct current flows in the saturating windings) to a low value (when full saturating direct current flows in the windings). Thus, the current supplied to the reactor saturating windings determines the voltage on the rectifier primary, and hence the output voltage of the rectifier.

The amount of this saturating current is controlled by a 3-element mercury vapor control tube T_1, and so the focal point of the whole control is the voltage applied between grid and cathode of this tube, which determines the amount of current it will pass; how, will be seen later. In this grid circuit are connected a phase-shift voltage *PS*, a standard voltage *G-G*, and a control, or comparison voltage. As may be seen, the control voltage is taken from the potentiometer, at points *A* and *B*. It is so connected that its polarity tends to act on the set to reduce the output voltage. In series with it, and opposing its effect, is the standard voltage; the difference between the 2 controls the set. This standard voltage is taken from a potentiometer across 2 glow tubes *G-G* connected in series. Each of these tubes maintains a constant voltage drop of about 90 volts over a considerable current range. They are supplied with a much higher d-c voltage, from a small rectifier through a high resistance, so that they will maintain 180 volts on the potentiometer over a large range of supply voltage. As the voltage regulation is obtained by the difference between the standard and control voltages only, it may be seen that the set will hold constant d-c output voltage regardless of line voltage fluctuations.

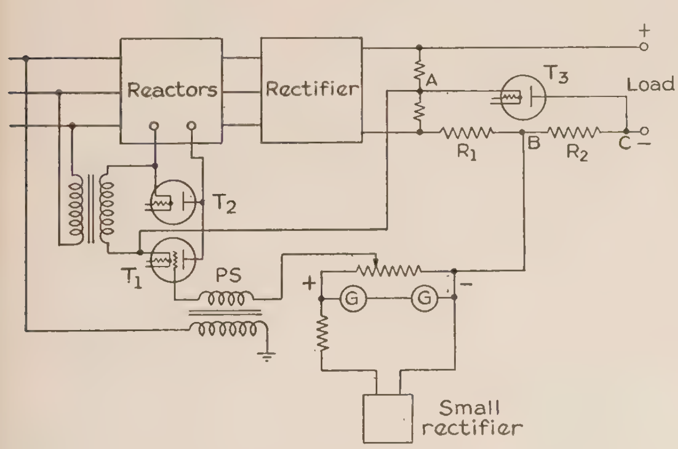


Fig. 1. Schematic diagram of component parts of vacuum tube controlled rectifier set

Resistor R_1 is the compound resistor. The voltage drop across it, due to the load current, acts against the control voltage, tending to raise the output voltage.

Resistor R_2 is the current-limiting control resistor. Point *C* is connected to point *A* through the rectifier tube, T_3. At no load, point *A* is the more positive, and current cannot flow through the rectifier from *A* to *C*. As the load current increases, the voltage drop across R_2 rises until point *C* becomes more positive than point *A;* current then flows through the rectifier from *C* to *A*, tending to raise the potential of point *A* and hence the control voltage, which acts to reduce the output voltage; thus the control is shifted from the voltage to the current at this point. Both R_1 and R_2 are variable, of course, because the current limit is adjustable, and it may be seen that at the current limit the IR drop in R_1 is approximately equal to the standard voltage. R_2 compensates for the drop in R_1.

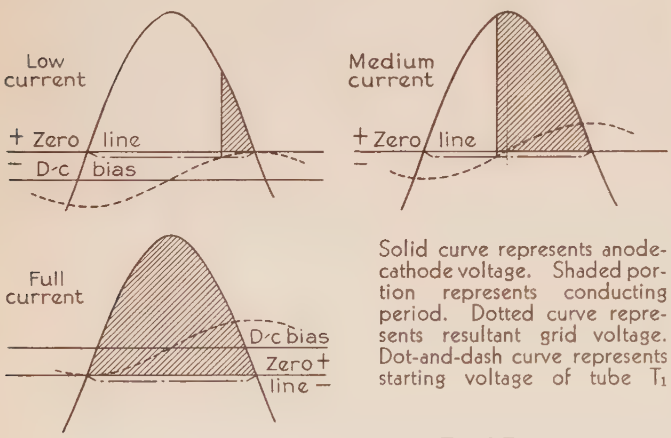
As has been said, the 3-element mercury vapor tube controls the amount of rectified alternating current fed into the saturating windings of the reactors. The a-c supply for this circuit is taken through an insulating transformer, in this case, because the negative point of the load and the neutral point of the supply are both grounded; if no insulating transformer were used, supply-line-to-ground voltage would be impressed across the control voltage. A "trailing tube" rectifier is placed across the saturating windings, to allow a lower saturating voltage to be used. As may be seen, when the transformer voltage is no longer in such a direction as to push current through the windings through T_1, the voltage induced in the winding due to its electromagnetic energy storage causes the stored energy to flow through T_2. This maintains saturation while T_1 is off.

Factors Limiting Precision of Control

We now come to the discussion of the factors influencing the precision of control obtainable with this system. Of course, in order to obtain the regulation desired there must be two conditions fulfilled; first, the a-c input voltage must always be above the maximum required for the application; and second, the reactor must have a maximum impedance high enough to limit the a-c voltage on the set to the lowest value required for the regulation. Having these fundamentals, the precision of control obtainable comes down, in the final analysis, to the voltage change on the grid of T_1 which will produce a change in the current it controls from zero to maximum saturating current. Using the tube without phase

shift on the grid, this difference is quite small (perhaps $^1/_{10}$ volt, depending on the tube). But if the tube is used without phase shift, it will "hunt," that is, as the voltage changes by a small amount the tube will turn either full on or full off, giving an effect on the reactor like that of a vibrating reed voltage regulator. Depending on the time constant of the circuit, the set will turn on for a few cycles, overshoot the desired voltage, turn off, drop below the desired voltage, and repeat, causing a slow ripple in the d-c output which may be objectionable. To overcome this, an a-c voltage is superimposed on the grid, lagging the anode voltage by 90 electrical degrees. This has the effect of causing the tube, as the d-c grid bias is raised, to turn on at first at the very end of the supply voltage positive half-cycle, then earlier and earlier, until finally it is conducting over all of the positive half-cycle. (See Fig. 2.) The d-c saturating current can thus be smoothly varied in proportion to the d-c bias on the grid; this makes the restoring force proportional to the unbalance, which gives an antihunting characteristic. But the larger the value of the phase shift voltage, the larger the change in d-c grid bias necessary to completely control the tube (see Fig. 2); so this a-c voltage should be as small as possible consistent with good antihunt characteristics. At this point, as in so many engineering solutions, a balance must be struck, a compromise effected.

Let us say, then, that a desirable compromise has been made, and that a given d-c grid bias change, x volts, completely controls the tube. The precision of the control will then be limited by the value of the standard. This may be readily seen from Fig. 3. For simplicity in explanation, let us say that when voltage A equals the standard voltage, the



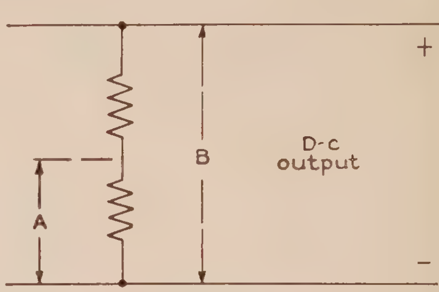
Solid curve represents anode-cathode voltage. Shaded portion represents conducting period. Dotted curve represents resultant grid voltage. Dot-and-dash curve represents starting voltage of tube T_1

Fig. 2. Phase control of tube T_1 of Fig. 1

balance point or control point is established. Now suppose a variation of load occurs which requires that the conduction angle of the tube be shifted from almost full off to full on, requiring x volts change in the value of the voltage across A. This means a change in the voltage across B of $(B/A)x$. Thus the larger the voltage across A (set by the standard voltage) the smaller the resultant change in B and the higher precision of control obtainable. Ordinarily a good precision of control is possible without going to high standard voltages; for example, in the set described here the regulation was 1 per cent, no load to full load, without compounding or compensation, using a standard of 180 volts. With compounding, this was reduced to $^1/_{10}$ or $^2/_{10}$ per cent over the whole range (without current limiting control). Even finer precision can be, and has been, easily obtained by amplifying the voltage difference between the standard and comparison voltages by a small vacuum tube before it is applied to the control tube grid.

The preceding discussion applies both to current regulation and voltage regulation, when applied singly; when both are applied together, the problem becomes a bit more complex. With the system used in the set described here, it may be seen that the load voltage is equal to the voltage across the potentiometer minus the voltage drop across the current limiting control resistor. At high voltages this drop is small compared to the total voltage, and can be compensated for by increasing the compounding resistor; the voltage drop of this resistor adds directly against the comparison voltage, and so raises the output voltage by an amount equal to its drop multiplied by the potentiometer ratio. This method was found satisfactory for the set described. If, however, the set on which the combination control is to operate is low voltage, high current, it is necessary to use another scheme; by using an additional small amplifying tube, a very small value of current-limiting resistor may be used.

Fig. 3. Schematic diagram of method of precision control



Conclusion

As this paper has shown, the very high precision of control obtainable with the system described makes it applicable to uses where close regulation is necessary. In addition, the almost unlimited range of current and voltage to which it may be applied, and the ease with which it works into an automatic control system, makes it seem likely that it will be used on a large variety of applications.

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The Theory of Incremental Rates and Their Practical Application to Load Division—Part II

Part I of this paper on incremental rates was published in ELECTRICAL ENGINEERING for March 1934, p. 432–45. The second and concluding part is presented herewith.

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Application to the Generating Station

IN the discussion so far, the operation of the boiler room and turbine room have been treated independently. It has been shown that in the usual case, the maximum turbine room efficiency is obtained when the turbine-generators are loaded incrementally and the maximum over-all boiler room efficiency when the boilers are loaded incrementally.

If the design of the station piping is such that all boilers feed into a common header, so that any boiler or group of boilers can supply steam to any turbine, then the maximum station efficiency will be obtained when the boilers and turbines are independently loaded so that all the turbines are operating at loads which correspond to the same turbine incremental rate and similarly all the boilers are operating at outputs which correspond to the same boiler incremental rate.

The mathematical proof of this statement is contained in Appendix B for the simple case consisting of only 2 boilers and turbines; the proof can easily be extended to include any number of turbines or boilers.

When the station design does not permit the flexibility of steam supply as stated above, the procedure should be modified depending upon the nature of the limitation. Three conditions of common occurrence are discussed below.

First Condition. If certain groups of turbines can be supplied with steam only by certain boilers, then the independent treatment of the entire boiler room and turbine room is not possible. In such a case it is necessary to compute the combined performance of each section of the station, consisting of a group of turbines and the particular group of boilers which supply them with steam. Each section is treated as an independent station and the turbine and boilers of that section loaded independently. The over-all station performance is obtained by dividing the total station load incrementally between the sections. It then becomes relatively a simple matter to compute the heat rate and incremental heat rate curves for the station.

Second Condition. Sometimes sections of a station are connected by a steam tie line of limited capacity. Appendix B shows that in such a case the boiler and turbine rooms may be treated independently until the limit of the tie line capacity is reached. Beyond this point, load division should be between sections until the capacity of either the boilers or turbines of one of the sections is reached.

To illustrate the procedure, consider the hypothetical set-up shown in Fig. 23*A* consisting of 2 turbines, each supplied by a group of boilers which are in parallel through a tie line of limited capacity. For the purposes of simplicity, the boiler outputs are expressed in megawatts referred to the generator terminals. Turbine-generators of 100 megawatts capacity each, with minimum operating loads of 25 megawatts, were assumed. Each group of boilers was assumed to have a capacity of 100 megawatts with a minimum operating load of 5 megawatts. The steam tie line was assumed to have

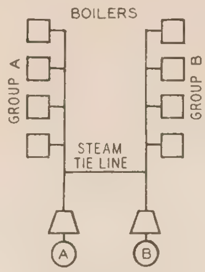

FIG. 23-A

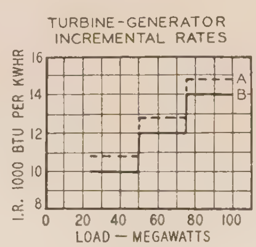

FIG. 23-B

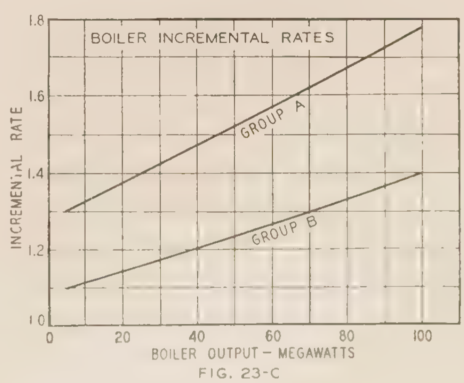

FIG. 23-C

Fig. 23. Performance curves of 2 groups of boilers connected by a steam tie line of limited capacity. (Used to illustrate method of loading turbine-generators and boilers)

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a limited capacity of 20 megawatts. The incremental rates for the turbine-generators and the corresponding groups of boilers are shown in Figs. 23*B* and Fig. 23*C*, respectively.

Table IV—Turbine and Boiler Load Division for Set-Up of Fig. 23A

Station Load	Turbine Loads: Unit A	Turbine Loads: Unit B	Boiler Output: Group A	Boiler Output: Group B	Steam Tie Line Load
50	25	25	5	45	20
55	25	30	5	50	20
60	25	35	5	55	20
65	25	40	5	60	20
70	25	45	5	65	20
75	25	50	5	70	20
80	30	50	7	73	23
85	35	50	9	76	26
90	40	50	11	79	29
95	45	50	13	82	32
100	50	50	15	85	35
105	50	55	17	88	33
110	50	60	19	91	31
115	50	65	21	94	29
120	50	70	23	97	27
125	50	75	25	100	25
130	55	75	30	100	25
135	60	75	35	100	25
140	65	75	40	100	25
145	70	75	45	100	25
150	75	75	50	100	25
155	75	80	55	100	20
160	75	85	60	100	15
165	75	90	65	100	10
170	75	95	70	100	5
175	75	100	75	100	0
180	80	100	80	100	0
185	85	100	85	100	0
190	90	100	90	100	0
195	95	100	95	100	0
200	100	100	100	100	0

All values in megawatts

Since the capacity of the steam tie line may be a limitation to the most economical load division, it is necessary to determine in what load range, if any, this limitation will occur. Table IV was prepared for the set-up used. The turbines and boilers were loaded incrementally and independently of each other. It is seen from Table IV that independent loading cannot be applied for station loads in the range from 75 megawatts to 155 megawatts. In this range of load, incremental rates for each section should be established and used as the basis for dividing the total load between sections.

Third Condition. Where 2 sections of a station operate at different steam pressures, then the use of a reducing valve and perhaps a steam desuperheater as a tie between the sections may introduce difficulties due to the complicated arrangements that may be necessary to return the feedwater from the low to the high pressure station. The procedure in such a case depends upon the piping arrangement of the station. It is interesting to note however, that up to the capacity of the reducing valve or desuperheater, the turbine room and boiler room may be treated independently in the manner discussed above, with the additional limitation that the flow of steam must be in one direction only. With capacity flow through the pressure-reducing device, each section should be considered as a unit and the total load divided between sections.

Corrections to Station Performance

Although the turbine heat rate and boiler efficiency are the 2 most important factors which determine station performance, there are several others which may have a considerable effect. The most important of these factors are auxiliary power, change in superheat and feedwater temperature with load, and seasonal variation in vacuum; sometimes heating steam or process steam must be considered. Allowance for these may be made by 1 of 2 methods: First, to correct the performance curves of the individual apparatus; and second, to make the correction on the station performance curves only. The first method is a laborious one which is perhaps justified only when the data available for computation purposes are adequate and

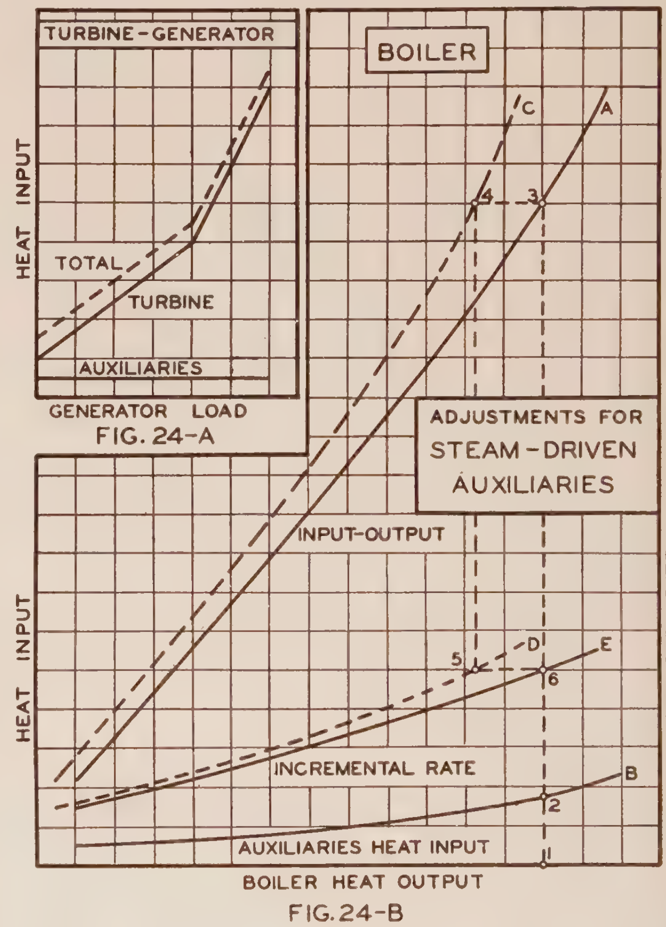

Fig. 24. Method of adjusting turbine-generator and boiler input-output curves for input to steam-driven auxiliaries

accurate, and when the performance for a great many different combinations of units is required. The second method requires less computation and can be used when a factor affects all of the equipment equally.

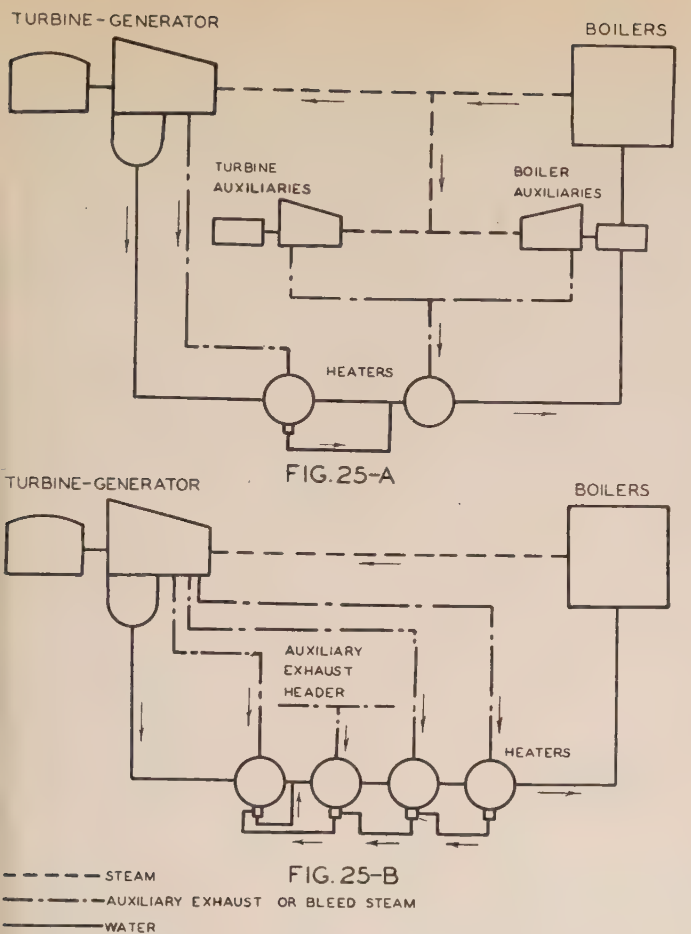

Fig. 25. Diagrams of typical heat balance cycles

Steam Auxiliaries

The auxiliary steam consumption varies with the load on the station and with the combination of boilers and turbines in operation. For load division purposes it usually is sufficiently accurate to group together the heat consumption of all steam auxiliaries and determine an average curve for the station. Then, for any station load, the boiler output would be the sum of the input to the turbines and the heat consumption of all the station steam auxiliaries. The boiler input for this value of boiler output would be found from the boiler input-output curve. Having determined the boiler inputs corresponding to the station loads, the station incremental rates and heat rates can be calculated.

Since the heat consumption chargeable against the auxiliaries is the heat input to the throttles of the auxiliary turbines less the heat recovered from the exhaust steam, the amount will vary depending upon the type and efficiency of the equipment utilizing the heat in the exhaust.

If the auxiliary steam requirements of different types of boilers or turbines in a station are radically different, use of one average auxiliary input curve for all combinations may not be desirable. When sufficient reasonably accurate data on individual auxiliary requirements are available, it is a simple matter to adjust the individual boiler and turbine input-output curves to include the auxiliary heat inputs.

For each turbine, the input for any given load is increased by the corresponding amount of the auxiliary heat consumption to give the equivalent turbine input required from the boilers. For each boiler the output for any given load is decreased by the corresponding auxiliary input, to give equivalent output available for use in the turbine room. The boiler incremental rate to be used in dividing load among the boilers will then be the slope of the curve showing the boiler input plotted against equivalent boiler output. The turbine incremental heat rate will be the slope of the curve of the combined heat input of the turbine and its auxiliaries plotted against turbine load.

The manner in which the input-output curves of the individual turbines and boilers are adjusted for the corresponding steam auxiliary heat consumptions is illustrated in Fig. 24*A* and *B*.

The foregoing method of correcting the individual turbine and boiler performance curves for their respective auxiliary heat consumptions can be correctly applied only if the exhaust steam is utilized after the turbine cycle is complete. A typical heat balance cycle which satisfies these conditions is illustrated in Fig. 25*A*.

In Fig. 25*B* is shown a heat balance diagram in which the exhaust steam enters the turbine cycle before a heater in which extracted steam is used. For a cycle of this kind, the heat consumption of the turbine from which extraction is made is affected by the amount and quality of the exhaust steam since these control the feedwater temperature entering the extraction heater thereby determining the amount of extracted steam. Hence, resort would have to be made to cut-and-try methods if it were desired to compensate for the variations in heat demand of auxiliaries of various units. The performance of any turbine would be affected by the number and loading of other turbines, and by the number and loading of the boilers in service.

An approximate solution could be made by establishing for each turbine 2 curves, both plotted against turbine-generator load. One would show the heat available for feedwater heating in the exhaust steam of the turbine auxiliaries; the other, the heat available in the exhaust of the boiler auxiliaries. The latter curve would be an approximate one, empirically determined by dividing the heat consumption of the boiler auxiliaries among the individual turbine-generators, so that for the normal sequence of operation, the sum of the quantities so assigned would equal the total heat consumption of the boiler auxiliaries through all ranges of station load. The 2 curves would be used to determine the input-output curve for each turbine. Once these were derived, the equivalent input-output curves of boilers and turbines would be computed in the manner already described.

Electric Auxiliaries

As in the case of steam auxiliaries, it is often most practical to group all of the electric auxiliaries together and determine an average total curve over the range of station load. A typical set of curves

for which an average was determined is shown in Fig. 26. Values from the total curve may be subtracted from the gross station output for any combination of units and the net station output be used to determine the station net heat rate and net incremental heat rate. If the load on the system is divided on the basis of gross station load, as is often the case, the station net heat rates and incremental rates should be plotted against gross station load.

If the auxiliary power requirements of the individual boilers and turbines are known, the input-output curves can be adjusted in a manner similar to that described for steam auxiliaries. Since the method to be used differs slightly with the different sources of auxiliary power, a solution for 3 cases commonly met with will be given below.

House Transformers

The effect of the station auxiliaries, when house transformers are used, is to reduce the station net output for a given total load on the main turbines. To obtain the maximum station efficiency it is necessary to make the station input a minimum for any given station *net* output. This requires that net rather than gross incremental rates be used in dividing load among the boilers and turbines.

For each turbine the net incremental heat rate is derived by subtracting from the generator output the corresponding amount of turbine auxiliary power, and determining the slope of the resulting net input-output curve. The turbine net incremental heat rate should be plotted against the generator load for use in dividing load among the turbines.

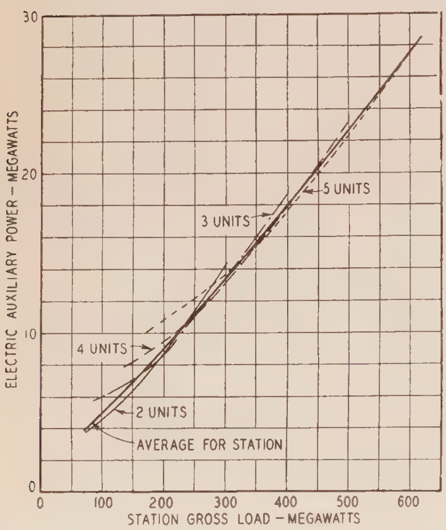

Fig. 26. Determination of average curve for station electric auxiliary power

For each boiler, the net incremental rate is derived by subtracting from the boiler output the equivalent *heat input* corresponding to the boiler auxiliary power and determining the slope of the resultant equivalent input-output curve. It will be noted, however, that the proper conversion factor to be used in reducing the kilowatt input to the boiler auxiliaries to Btu per hour input is the prevailing turbine incremental heat rate. In order to visualize the steps in the process, consider a boiler which is supplying steam to operate a turbine at a given load and assume that there is no auxiliary power being used by the boiler. Then, in order to produce the same net load when the boiler does require auxiliary power, the load on the turbine would have to be increased by a corresponding amount.

This increase in turbine-generator load is nothing more than an "incremental output" for which the corresponding "incremental input" is the product of the boiler auxiliary power and the turbine-generator incremental heat rate. Since the turbine-generator incremental heat rate is not a function of the boiler load, but depends upon the number and loading of the turbine-generators in service, it would be difficult to ascertain the prevailing turbine-generator incremental heat rate for converting the boiler auxiliary power into equivalent heat units. The use of an average value of turbine-generator incremental heat rate in place of the prevailing value is recommended as being simple, without introducing great error.

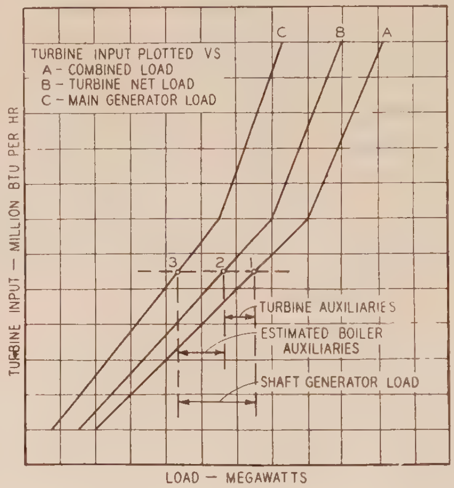

Fig. 27. Adjustment of turbine input-output curve for load on shaft generator

House Generators

When station auxiliary power is obtained from house generators on the shafts of the main turbines, it may be difficult to establish an exact relation between the outputs of the house and main generators. Since the output of the house generator is small compared to that of the main generator, the error in assuming its efficiency to equal that of the main generator is negligible. Thus it may be assumed that the heat input to the turbine is a function of the total load on the 2 generators and is independent of the division of load between them.

The net turbine-generator load which is the combined load less the electric power consumption of the turbine auxiliaries, should be used in finding the turbine incremental rate. Since the actual assignment of load to a turbine is usually made in terms of load on the main generator, the division of load between the main and shaft generators must be estimated. This can be done by assuming average conditions in the boiler room and allocating

to each turbine a share of the boiler room electric auxiliary power which, added to the turbine-generator auxiliary power, gives the shaft generator load. Referring to Fig. 27, curves A, B, and C represent the input to the turbine plotted, respectively, against the combined load, turbine-generator net load, and main generator load. For purposes of load division in the turbine room, the incremental rates of curve B should be plotted against the corresponding load values of curve C. Thus the incremental rate at point 2 will be plotted against the load at point 3. The resulting curve would then show the turbine-generator net incremental rate plotted against the main generator load, and should be used in conjunction with the incremental curves of other turbine-generators to determine the turbine loading.

House Turbine-Generators, Noncondensing Type

Where house turbine-generators of the non-condensing type are used to supply electrically driven auxiliaries, the output of the house generator should be divided between the boilers and turbines. The electric power consumption of the auxiliaries should be converted into equivalent heat values and added to the turbine inputs and subtracted from the boiler outputs in the manner indicated in the discussion for steam driven auxiliaries. The conversion factor in this case, however, should be the corresponding value of the house turbine heat rate. An average value of house turbine-generator heat rate may be used if it is difficult to ascertain the instantaneous values.

In computing the heat rate of the house turbines when the exhaust steam is used to heat the feedwater, the heat reclaimed in the feedwater must not be charged against the auxiliaries. Furthermore, if the exhaust steam enters the turbine cycle, and affects the amount of steam extracted for feedheating, it will be necessary to make computations similar to those described for the same conditions in the discussion of steam auxiliaries.

House Turbine-Generators, Condensing Type

If the house turbines are of the condensing type the condensate from the main turbines is often used circulating water in the house turbine condenser; the house turbine condensate will be mixed with the main condensate, and go through the heaters of the main turbine. Thus, the heat consumption of the main turbines at any given load will be affected by the amount of auxiliary power required by the boilers and turbines. This introduces the same complication that was described for the case in which the exhaust steam from auxiliaries entered the turbine cycle; similar methods of solution are necessary.

Superheat and Feedwater Temperature

It is rarely that boilers give a constant superheat throughout their full load ranges. The superheat is usually affected by the percentage rating at which the boiler is run, the fire conditions, and the temperature of the feedwater into the boiler. The feedwater temperature into the boiler may be partially or wholly dependent upon the total station load and the number and loading of the turbines on the line. It is sometimes, however, kept constant by means of thermostatically operated pressure-reducing valves on the highest pressure heaters, or by the use of exhaust steam in an open heater to bring it to the final temperature.

Correction of station performance for the effect of feedwater temperature is rather an involved and complicated matter. A change in feedwater temperature will result in a change in the superheat of the steam delivered by the boiler to the turbine, which in turn will affect the performance of the latter. Thus it becomes necessary to correct not only the boiler performance but also the turbine performance for the effect of a change in feedwater temperature supplied to the boiler.

Superheat Correction, Feedwater Temperature Constant

When the station feedwater temperature is constant, the correction for the effect of variation of superheat on turbine performance need be applied only to the boiler performance curves.

The economy of operation of a turbine is affected by the temperature of the steam supplied to the throttle. For a given quantity of steam supplied per hour, a decrease in temperature results in a decrease in turbine output, and an increase in temperature results in an increase in output. Consequently, although 2 boilers are operating in parallel with equal efficiencies, if their steam temperatures are not the same, the steam at the lower temperature is used less efficiently in the turbine than the steam at the higher temperature. It is evident that some adjustment is necessary for the better economy obtained in the turbine from steam at the higher temperature. This can be done by calculating the turbine performance for a fixed steam temperature at the throttle and then adjusting the individual boiler efficiency curves for the variation of their steam temperatures from this fixed value. If there are large drops in steam temperature and pressure between the boiler outlet and turbine throttle, these should be allowed for in selecting the fixed temperatures used as the basis for adjusting the turbine and boiler performance curves.

The turbine performance correction factor may be given as a correction to the heat rate or to the water rate. It is much simpler to apply to the heat rate but for many of the older turbines only the water rate correction is available. It must be remembered that an increase in steam temperature which gives one per cent decrease in water rate does not give the same decrease in heat rate, since the heat content per pound of steam at the throttle is substantially increased, so that the total decrease in heat rate may be less than 0.5 per cent. If the superheat correction factors vary but slightly for the different machines an average factor may be used. If there is considerable variation, a better

method is to determine for each turbine the group of boilers which normally supply it with steam, using the superheat correction factor of each turbine for adjustment of the performance curves of the corresponding group of boilers.

To illustrate the method of adjusting the boiler performance curve, consider a boiler which is furnishing steam to a turbine at constant pressure and is receiving feedwater at a constant temperature. Let

T_s = standard steam temperature to which turbine and boiler performances are corrected, degrees Fahrenheit
T_a = actual steam temperature at turbine throttle, degrees Fahrenheit
W_s = turbine steam consumption at standard temperature corresponding to some given load, pounds per hour
W_a = turbine steam consumption at actual steam temperature and same load, pounds per hour
B_a = actual boiler output required when steam is at temperature T_a, Btu per hour
B_s = equivalent boiler output which would be required if steam were at the temperature T_s, Btu per hour
H_s = total heat of steam at temperature T_s, Btu per pound
H_a = total heat of steam at temperature T_a, Btu per pound
q = heat of liquid of feedwater into boiler, Btu per pound
k = turbine steam consumption correction factor for variation of superheat at throttle

Then

$$B_s = W_s(H_s - q)$$

$$B_a = W_a(H_a - q)$$

$$= W_s[1 + k(T_s - T_a)](H_a - q)$$

and

$$\frac{B_s}{B_a} = \frac{(H_s - q)}{[1 + k(T_s - T_a)](H_a - q)}$$

Since B_s is the boiler output at the standard temperature T_s which would do the same work in the turbine as the actual output B_a, the equivalent efficiency of the boiler may be defined as the ratio of B_s to the actual boiler input. Let E_a and E_s be the actual and equivalent boiler efficiencies, respectively.

Then

$$E_s = \frac{B_s \times E_a}{B_a} = \frac{E_a(H_s - q)}{[1 + k(T_s - T_a)](H_a - q)}$$

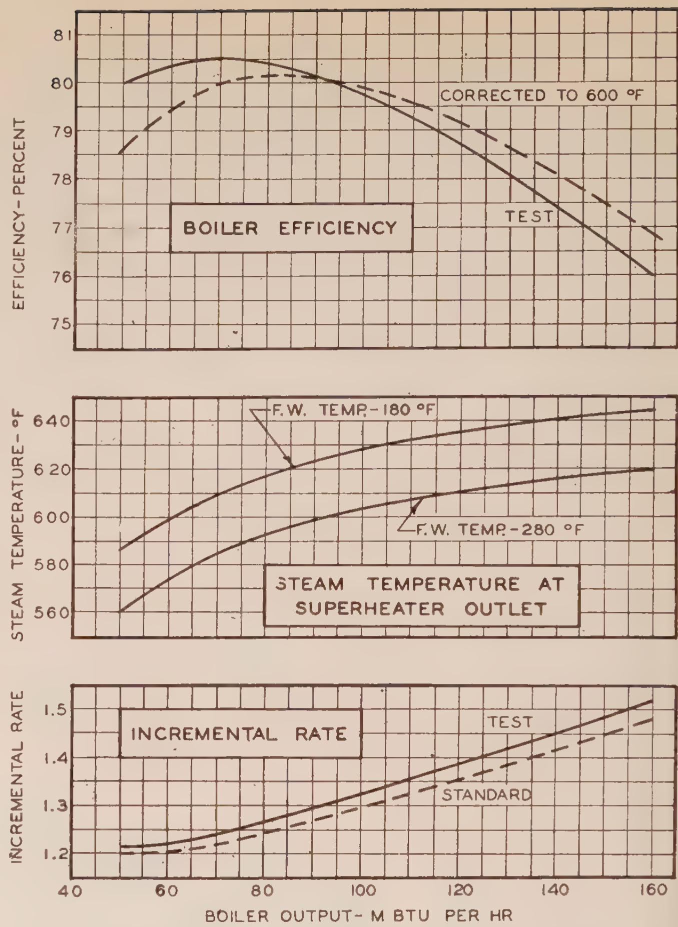

Fig. 28. Adjustment of boiler efficiency and incremental rate curves for feedwater temperature variation

M Btu indicates million Btu

When several boilers supply steam at different temperatures to a common header, the resultant temperature of the steam entering the turbine may be different from that at any boiler outlet. Adjustment of the boiler curves for variation in superheat is made as if the temperature of the steam entering the turbine is the same as that leaving the boiler. This is equivalent to assuming that when several quantities of steam having the same pres-

Table V—Superheat Adjustment of Boiler Performance

B_a	T_t	T_a	$T_s - T_a$	$1 + k(T_s - T_a)$	H_a	$H_a - q_s$	B_s/B_a	B_s	E_a	E_s
50	585	560	40	1.040	1291.2	1042.2	0.9819	49.1	80.00	78.55
60	599	574	26	1.026	1299.0	1050.0	0.9879	59.3	80.35	79.38
70	610	585	15	1.015	1305.0	1056.0	0.9930	69.5	80.50	79.94
80	618	593	7	1.007	1309.4	1060.4	0.9967	79.7	80.42	80.15
90	624	599	1	1.001	1312.7	1063.7	0.9995	90.0	80.14	80.10
100	629	604	−4	0.996	1315.5	1066.5	1.0020	100.2	79.74	79.90
110	633	608	−8	0.992	1317.7	1068.7	1.0039	110.4	79.23	79.54
120	636	611	−11	0.989	1319.3	1070.3	1.0055	120.7	78.66	79.09
130	639	614	−14	0.986	1320.9	1071.9	1.0070	130.9	78.00	78.55
140	641	616	−16	0.984	1322.0	1073.0	1.0080	141.1	77.39	78.01
150	643	618	−18	0.982	1323.1	1074.1	1.0090	151.4	76.71	77.40
160	645	620	−20	0.980	1324.2	1075.2	1.0101	161.6	75.99	76.76

T_s = 600 deg F
t_s = 280 deg F
t_t = 180 deg F
Pressure = 300 lb abs.

H_s = 1313.3 Btu/lb
q_s = 249.0 Btu/lb
$H_s - q_s$ = 1064.3 Btu/lb
k = 1 per cent for 10 deg F

$T_t - T_a = 0.25(t_s - t_t) = 0.25(280 - 180) = 25$ deg F

$$B_s/B_a = \frac{H_s - q_s}{[1 + k(T_s - T_a)](H_a - q_s)} = E_s/E_a$$

T_t is the steam temperature obtained on boiler test with a feedwater temperature t_t; t_s is the standard feedwater temperature to which boiler performance is adjusted

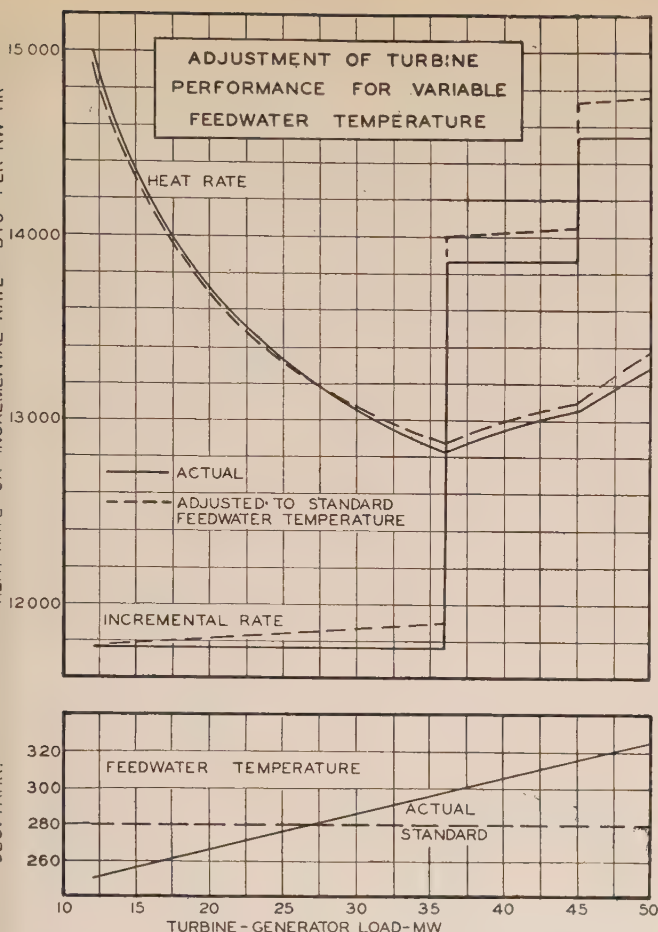

Fig. 29. Adjustment of turbine-generator heat and incremental heat rate curves for variation of feedwater temperature supplied to boilers

Mw indicates megawatts

ure but different temperatures are mixed, the resultant temperature may be obtained by taking the average, weighted according to the amount of heat contained in each quantity of steam. The error introduced by adjusting the boiler curves in the manner described here is within the accuracy with which the superheat curves of individual boilers can be determined.

Superheat Correction, Feedwater Temperature Variable

When the boiler is called upon to evaporate feedwater at variable temperatures, the fact that at a given load the steam will not always be delivered with the same superheat makes it difficult to determine a characteristic curve of superheat against heat output.

The effect of feedwater temperature on boiler performance is further complicated when economizers are used on the boilers. The hotter the feedwater entering the economizer the less heat is recovered from the flue gases. The loss in economizer efficiency is cumulative with the loss due to lowering the superheat, and may be several times as great as the latter.

Thus there are 3 different conditions that might prevail in a station having variable feedwater temperature. It might be that:

1. None of the boilers were equipped with economizers.
2. All of the boilers were equipped with economizers.
3. Some of the boilers had economizers while others had none.

The cases are cited in the order of their relative simplicity of treatment.

Boilers Without Economizers

In case of a station having no economizers on the boilers, the change in superheat with change in feedwater temperature is the only consideration. Some knowledge of the relationship existing between the feedwater temperature and the superheat for the particular boilers is necessary. This will depend upon the type and size of the superheaters installed; it may differ somewhat among the boilers, in which case a weighted average can be taken.

The boiler superheat characteristic should be corrected to a condition of constant feedwater temperature; the input-output curve and incremental rate should then be adjusted to compensate for the deviation of the new superheat characteristic from the standard superheat.

In the same way, the turbine performance will be

Table VI—The Adjustment of Turbine Performance for Feedwater Temperature

Load, Megawatts	t_a	$t_s - t_a$	$T_s - T'_a$	T'_a	$1 + k(T_s - T'_a)$	H'_a	q_a	$H'_a - q_a$	$H_s - q_a$	HR'_a/HR_s	HR_s	HR'_a
12	251	+29	− 7.3	607.3	0.9927	1317.3	219.4	1097.9	1093.9	0.9963	15000	14945
18	263	+17	− 4.3	604.3	0.9957	1315.6	231.6	1084.0	1081.7	0.9978	13923	13892
24	275	+ 5	− 1.3	601.3	0.9987	1314.0	243.8	1070.2	1069.5	0.9994	13385	13377
30	286	− 6	+ 1.5	598.5	1.0015	1312.5	255.1	1057.4	1058.2	1.0007	13063	13072
36	298	−18	+ 4.5	595.5	1.0045	1310.8	267.4	1043.4	1045.9	1.0021	12847	12874
40	306	−26	+ 6.5	593.5	1.0065	1309.7	275.7	1034.0	1037.6	1.0030	12949	12988
45	316	−36	+ 9.0	591.0	1.0090	1308.3	286.0	1022.3	1027.3	1.0041	13051	13105
47	320	−40	+10.0	590.0	1.0100	1307.8	290.2	1017.6	1023.1	1.0046	13157	13218
50	326	−46	+11.5	588.5	1.0115	1307.0	296.4	1010.6	1016.9	1.0052	13300	13369

$_s$ = 600 deg F $\quad H_s$ = 1,313.3 Btu/lb

= 280 deg F $\quad$ Pressure = 300 lb abs

= 1 per cent for 10 deg F $\quad T_s - T'_a = -0.25(t_s - t_a)$

$$HR'_a/HR_s = \frac{[1 + k(T_s - T'_a)](H'_a - q_a)}{H_s - q_a}$$

and t_a are, respectively, the standard and the actual feedwater temperatures. If the boiler in Table V were supplying steam at the standard steam temperature $_s$ with the standard feedwater t_s, changing the feedwater temperature to the actual turbine feedwater temperature t_a would cause the steam temperature to change the adjusted value T'_a. HR_s and HR'_a are the turbine heat rates with steam at the temperature T_s and T'_a, respectively

corrected to the average superheat; it will be further corrected for the effect of its feedwater temperature characteristic on the superheat of the steam, generated in the boilers, and hence on its own economy.

In Table V are shown computations for adjusting the boiler performance curves of Fig. 28 from actual to standard conditions of steam and feedwater temperatures. Table VI shows computations for adjusting the turbine performance curves of Fig. 29 for the variation of the feedwater temperature from standard.

Economizers on All Boilers

The effect of varying feedwater temperature on the performance of boilers which are equipped with economizers may be several times as great as the effect on boilers without them. Since the amount of heat recovered in the economizer changes considerably with change in feedwater temperature, the boiler efficiency at any given heat input is dependent upon this temperature. The effect of change in feedwater temperature on the boiler superheat, however, is less when there is an economizer than when the feedwater goes directly into the boiler. The change in superheat and change in efficiency of the boiler unit per degree Fahrenheit change in feedwater temperature into the economizer should be determined for each type of installation. This is best done experimentally rather than by use of guarantee data.

Correction of the boiler performance curves to standard feedwater and steam temperatures is made in 3 steps:

1. Correction of the efficiency of the boiler unit for the effect on the heat recovery in the economizer caused by changing the feedwater temperature to standard.
2. Correction of the boiler superheat characteristic to a condition of standard feedwater temperature.
3. Adjustment of the efficiency curve obtained in (1) for variation of the superheat characteristic of (2) from the standard superheat.

Correction of the turbine performance curves is also made in 3 steps:

1. The turbine heat rate is corrected to the standard steam temperature.
2. Correction of the heat rate curve from (1) for the effect on the *turbine* efficiency, of the variation of the boiler superheat resulting from the difference of the actual turbine feedwater temperature from the standard.
3. Adjustment of the heat rate curve from (2) for the effect on the *boiler* efficiency, of the variation of the actual turbine feedwater temperature from the standard.

Some Boilers With Economizers, Some Without

In this case the performance curves of each individual boiler are adjusted as was described above, using the proper correction factors. In making the adjustment of the turbine performance curves the most feasible solution is to use the correction factors corresponding to the group of boilers from which it normally receives most of its steam.

Seasonal Variation in Vacuum

Since the variation of vacuum with turbine load has a marked effect on the incremental rate, this variation should be taken into account in establishing the turbine input-output curves.

The seasonal change in circulating water temperature causes a change in the vacuum-load characteristics and hence the incremental rates of the individual turbine, but in many instances it will be found that load division between the turbines is not disturbed because all of the units are affected relatively to the same extent. Under these conditions, use of vacuum-load curves corrected to the yearly average circulating water temperature will be sufficiently accurate.

When the seasonal change in circulating water temperature is not the same for all of the stations in a system, or when some turbines are much more sensitive than others to change in circulating water temperature, a series of performance curves may be established for use during different periods of the year.

Heating and Process Steam

When stations supply heating or process steam in large quantities, as well as power, the load division procedure may get too complicated for more than an approximate solution. Where high pressure steam is sold, it is possible that one or more of the boilers of the station will be isolated to supply only the steam for sale. In this case the only effect on the power boilers may be to decrease the number available and hence increase the incremental rate for a given turbine demand.

When the same boilers supply steam both for power and heating, an approximate solution can be made by determining the kilowatt load equivalent to the heating steam. For purposes of system load division, the system demand is considered to include the heating steam equivalent load; the actual load which should be generated by the station supplying the heating steam is the assigned load less the equivalent load of the heating steam. The heating steam can be converted into an equivalent load by dividing the heat in the steam by the average turbine incremental heat rate.

The problem of obtaining the correct load division becomes very complicated when heating or process steam is supplied from the turbine exhaust or by extraction. The solution depends upon the heat balance cycle as well as on operating conditions such as whether the amount of process steam required is variable or constant and whether it is necessary to keep the load on the turbines supplying the steam constant or always above a certain value, in order to maintain the required process steam temperature. Change in the amount of heating steam will change the incremental heat rates as well as the loads at which the admission valves become fully open.

Because each problem depends so closely upon the individual set-up, no solution will be included here. It is felt that the methods discussed for other cases

an be extended to take care of the majority of problems involving the extraction of steam for commercial ses.

MAINTENANCE

The operation of equipment, especially boilers, t or near maximum capacity may result in excessive maintenance costs for the equipment. The oads above which the maintenance costs increase apidly should be determined and considered as ormal operating limits, or else the incremental ates of the equipment in question should be arbirarily increased for all loads above the one at which he maintenance costs become excessive.

If 2 or more interconnected generating stations ave maintenance costs which differ considerably,

Table VII—Computation of Boiler Inputs Using Incremental Rates

Boiler Output Million Btu/Hr	Incremental Output Million Btu/Hr	Average Incremental Rate	Incremental Input Million Btu/Hr	Boiler Input Million Btu/Hr
2,100				2358.0
	100	1.152	115.2	
2,200				2473.2
	100	1.162	116.2	
2,300				2589.4
	100	1.173	117.3	
2,400				2706.7
	100	1.185	118.5	
2,500				2825.2
	100	1.198	119.8	
2,600				2945.0
	100	1.202	120.2	
2,700				3065.2
	100	1.217	121.7	
2,800				3186.9
	100	1.233	123.3	
2,900				3310.2
	100	1.250	125.0	
3,000				3435.2
	100	1.268	126.8	
3,100				3562.0
	100	1.287	128.7	
3,200				3690.7
	100	1.307	130.7	
3,300				3821.4
	100	1.328	132.8	
3,400				3954.2
	100	1.350	135.0	
3,500				4089.2
	100	1.373	137.3	
3,600				4226.5
	100	1.397	139.7	
3,700				4366.2
	100	1.422	142.2	
3,800				4508.4
	100	1.448	144.8	
3,900				4653.2
	100	1.475	147.5	
4,000				4800.7

hen it is not correct procedure to divide the common oad among them on the basis of their respective ncremental heat rates. The respective incremental naintenance costs should be determined and conerted into equivalent heat units which, added to the orresponding incremental heat rates, will give the djusted incremental heat rate curves that should be sed to determine the division of load.

The adjustment for maintenance must be made mpirically because no definite relationship between incremental maintenance costs and instantaneous values of load is known.

COMPUTATION OF STATION PERFORMANCE

After having selected the specific method of computing the performance of the individual equipment in the station, and having carried through the computations, making any necessary corrections for auxiliary power, feedwater temperature, and steam superheat, the station input-output and incremental rate curves are determined. For any desired turbine and boiler combination, the turbine room input-output curve should be calculated, and then combined with the boiler curves to give the station performance.

Very great care must be taken in drawing the input-output curves, in order to get consistent incremental rate curves. If a great many combinations of turbines and boilers are required, accuracy sometimes can best be secured by using input-output tables instead of curves, interpolating, if necessary, to obtain values that are not tabulated. In constructing the tables, the approximate input-output curve should be drawn; the incremental rate curve should be determined and carefully adjusted so that it is consistent and so that the area included under it, represents the difference between the maximum and minimum inputs. By selecting convenient values of incremental output and multiplying them by their respective average values of the incremental rate, the corresponding incremental inputs are obtained, which, added cumulatively to the minimum input, give successive values of input. A sample computation using this method is shown in Table VII for a group of boilers.

Whether or not the expenditure of the time and labor required for a rigorous calculation of station performance is justified, depends upon the use that is to be made of the computations. If the use is solely for load division purposes, it is doubtful whether a rigorous calculation can be justified, because the variation in the loading of generating stations within reasonable limits, will not appreciably affect the over-all production costs of the system. When considerable work is done in station heat balance computation, however, as is often the case for large modern steam generating stations, a detailed computation arranged so that it can easily be applied under widely divergent conditions of operation, may be a very profitable undertaking.

APPROXIMATE METHOD OF CALCULATING STATION PERFORMANCE

An approximate method for computing station performance curves has been developed which is very simple to apply and which permits the computation of curves for numerous combinations of boilers and turbine-generators in relatively little time. This method should have extensive use in cases where rigorous calculations cannot be justified.

In this method performance curves, similar to those shown in Fig. 30, are established for the turbine room, boiler room, and steam and electric

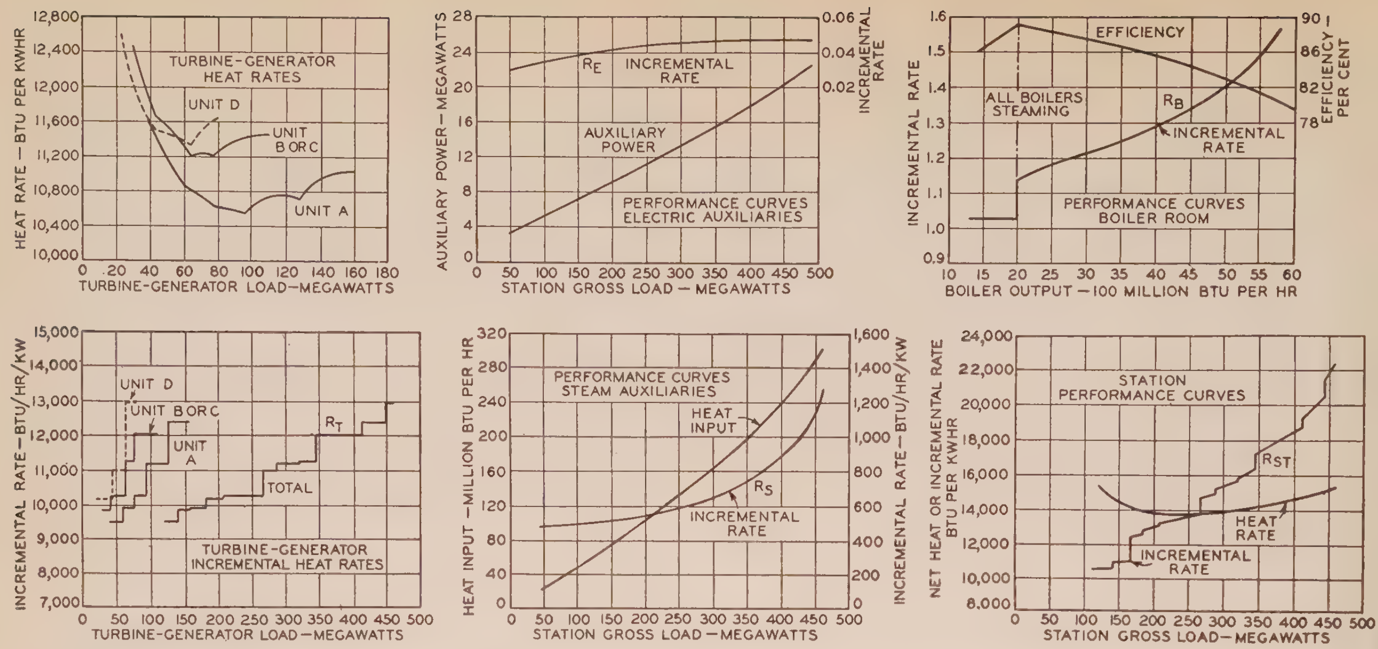

Fig. 30. Performance curves required for the calculation of station incremental heat rates by an approximate method

auxiliaries. The station incremental rates can then be derived from the incremental rates of the above-mentioned equipment by means of the relation:

$$R_{ST} = \frac{R_B(R_T + R_S)}{1 - R_E}$$

Where

R_{ST} = station incremental rate
R_B = boiler room incremental rate
R_T = turbine room incremental rate
R_S = incremental rate of steam auxiliaries
R_E = incremental rate of electric auxiliaries

A sample computation in which this method was applied is shown in Table VIII. The station heat rates can be computed from the net station loads, the total boiler room output (which is the sum of the inputs to the steam auxiliaries and main turbines) and the boiler room efficiency. The latter was derived in the manner illustrated in Table VII.

It should be noted that the boiler room incremental rate curve for the banked boiler region cannot be determined directly from the individual boiler incremental rates, but must be derived from an average input-output curve for the banked range of the boiler combination in question. In many cases sufficient accuracy can be had by computing the input at the minimum required boiler output, and at the point at which the last boiler is taken off bank. The difference in input divided by the corresponding difference in output gives the average incremental rate which should be used in the banked boiler region.

The derivation of the above relation, included in Appendix C, is based upon the assumption that the electric and steam auxiliaries are both functions of the gross station load only. This assumption is not strictly correct but as was indicated in the previous discussion on station auxiliaries, is sufficiently accurate for most purposes.

If the station auxiliaries are essentially steam driven, then the probability is that the electric auxiliary power is practically constant and independent of the station load. The incremental rate of the electric auxiliaries is zero, and the relation becomes

$$R_{ST} = R_B(R_T + R_S)$$

Likewise when the station auxiliaries are essentially electrically driven and the input to the steam auxiliaries is relatively constant, the incremental rate of the steam auxiliaries is zero, and the relation becomes

$$R_{ST} = \frac{R_B R_T}{1 - R_E}$$

Load Division Between Generating Stations

Assuming the performance of each generating station in an interconnected system has been established, taking into account such factors as coal cost, circulating water conditions, and maintenance, the problem then arises of how to load the stations to get the best system economy. Load division between stations is usually limited by such factors as tie-feeder capacity, voltage and power factor regulation, and safety of operation.

The problem of load division, when the transmission line losses are negligible, becomes merely one of operating the stations at equal incremental rates. On the other hand, if the losses are appreciable, the load division procedure must be modified to take them into account. To illustrate the effect of tie line losses, the simplest case to consider is that for 2 interconnected generating stations. In order that it be economical to transfer a given load from one station to another, the following relation must prevail

$$R_s = R_r \times E_{tl}$$

Where

R_s = incremental rate of the sending station
R_r = incremental rate of the receiving station

$_{tl}$ = incremental efficiency of the transmission line corresponding to the given load transferred

Analysis of the above equation, which is derived 1 Appendix D, shows that in the case of inter- onnected generating stations the general rule is orrected to include a factor E_{tl}, the incremental fficiency of the transmission line. The latter is a inction of the line losses, being the increment of oad at the receiving end divided by the increment of oad at the sending end.

When several stations are linked together, it nay be impossible to determine the loading which vill give maximum over-all efficiency except by trial- nd-error computations. Any detailed analysis de- ends so much upon the physical set-up of the in- ividual system, that none will be included here. 'he principles to be applied are the same as those vhich govern load division within the station, amely, to keep individual stations operating as losely as possible at the same incremental rates, aking into account transmission line losses. (A nore complete discussion of the effect of transmission ine losses is given by the article "Incremental Load- ng of Generating Stations," by M. J. Steinberg and '. H. Smith, ELEC. ENGG., October 1933, p. 674–7.)

When a system contains several large generating tations with many turbine-generator units, the roblem of selecting the correct combination of units or a given system load resolves itself into 2 parts:

1. Determination of the order in which units should be added to the line at each individual station, as the *station* load increases.

2. Determination of the order in which units should be put in service throughout the system, as the *system* load increases.

Since, at a given time, the same group of boilers will be used to supply steam to any combination of units in an individual station, the sequence in which units should be added is in the order of their relative efficiencies. Thus to determine the proper combination at a given station load, it is only necessary to plot the turbine heat rate curves of successive combinations and select the one which gives the lowest turbine input. When several stations are operating in parallel, units put on the line at one station must get their steam from the boilers of that station, hence the total boiler input of the system must be used as the criterion in adding units, not the total turbine input. Calculation of the system input for several combinations will be required before the proper one can be ascertained for the given system load.

Computation of the system inputs for each of the numerous combinations, which requires a great deal of time and labor, can be eliminated by applying the following method:

1. For each individual station, compute the station input-output curves corresponding to the proper sequence of adding units.

2. Plot the curves of (1) and draw an average input-output curve through them.

Table VIII—Sample Calculation of Station Performance Curves

Turbine-Generator Loads, Megawatts: A	B	C	D	Total	Elec. Aux. Power Megawatts	Station Net Load Megawatts	Turbine Inputs, Million Btu/Hr: A	B	C	D	Steam Aux. Input, Million Btu/Hr	Total Boiler Room Output, Million Btu/Hr	R_T	R_B	R_E	R_S	R_{ST}	Boiler Room Eff. Per Cent	Station Net Heat Rate Btu/Kwhr
40	30	30	20	120	6.1	113.9	461	373	373	261	60	1,528		1.028	0.036	500	10,670	86.8	15,450
50	30	30	20	130	6.5	123.5	555	373	373	261	65	1,627	9,510	1.028	0.036	510	10,690	87.2	15,410
60	30	30	20	140	6.9	133.1	651	373	373	261	70	1,728		1.028	0.037	520	10,710	87.8	14,790
60	30	30	20	140	6.9	133.1	651	373	373	261	70	1,728		1.028	0.037	520	11,080	87.8	14,790
60	43	30	20	153	7.4	145.6	651	501	373	261	78	1,864	9,860	1.028	0.038	520	11,090	88.5	14,460
60	43	43	20	166	7.9	158.1	651	501	501	261	85	1,999		1.028	0.038	520	11,090	89.0	14,210
60	43	43	20	166	7.9	158.1	651	501	501	261	85	1,999		1.140	0.038	520	12,490	89.0	14,210
70	43	43	20	176	8.2	167.8	752	501	501	261	90	2,105	9,920	1.148	0.039	530	12,600	89.0	14,090
78	43	43	20	184	8.6	175.4	830	501	501	261	95	2,188		1.156	0.040	540	12,720	88.9	14,030
78	43	43	20	184	8.6	175.4	830	501	501	261	95	2,188		1.156	0.040	540	12,910	88.9	14,030
78	43	43	30	194	9.0	185.0	830	501	501	359	100	2,291	10,180	1.172	0.041	540	13,100	88.8	13,950
78	43	43	44	208	9.6	198.4	830	501	501	505	108	2,445		1.184	0.041	550	13,250	88.5	13,930
78	43	43	44	208	9.6	198.4	830	501	501	505	108	2,445		1.184	0.041	550	13,350	88.5	13,930
85	43	43	44	215	9.9	205.1	902	501	501	505	112	2,521	10,260	1.187	0.042	560	13,410	88.4	13,910
96	43	43	44	226	10.3	215.7	1,014	501	501	505	118	2,639		1.194	0.042	560	13,490	88.2	13,870
96	43	43	44	226	10.3	215.7	1,014	501	501	505	118	2,639		1.194	0.042	560	13,490	88.2	13,870
96	64	43	44	247	11.3	235.7	1,014	717	501	505	131	2,868	10,260	1.210	0.043	580	13,710	87.7	13,870
96	64	64	44	268	12.1	255.9	1,014	717	717	505	142	3,095		1.221	0.044	600	13,870	87.3	13,850
96	64	64	44	268	12.1	255.9	1,014	717	717	505	142	3,095		1.221	0.044	600	14,800	87.3	13,850
96	64	64	55	279	12.5	266.5	1,014	717	717	629	149	3,226	10,990	1.230	0.045	620	14,950	87.1	13,900
96	64	64	64	288	12.9	275.1	1,014	717	717	725	155	3,328		1.236	0.045	630	15,040	86.9	13,920
96	64	64	64	288	12.9	275.1	1,014	717	717	725	155	3,328		1.236	0.045	630	15,300	86.9	13,920
110	64	64	64	302	13.6	288.4	1,182	717	717	725	164	3,505	11,190	1.250	0.045	650	15,500	86.5	14,050
128	64	64	64	320	14.4	305.6	1,372	717	717	725	176	3,707		1.265	0.046	680	15,740	86.1	14,090
128	64	64	64	320	14.4	305.6	1,372	717	717	725	176	3,707		1.265	0.046	680	15,830	86.1	14,090
128	77	64	64	333	14.9	318.1	1,372	863	717	725	185	3,862	11,260	1.280	0.046	700	16,050	85.8	14,150
128	77	77	64	346	15.5	330.5	1,372	863	863	725	195	4,018		1.293	0.046	730	16,250	85.4	14,240
128	77	77	64	346	15.5	330.5	1,372	863	863	725	195	4,018		1.293	0.046	730	17,290	85.4	14,240
128	110	77	64	379	17.2	361.8	1,372	1,260	1,863	725	224	4,444	12,030	1.343	0.047	820	18,110	84.3	14,570
128	110	110	64	412	18.6	393.4	1,372	1,260	1,260	725	249	4,866		1.386	0.047	920	18,830	83.3	14,850
128	110	110	64	412	18.6	393.4	1,372	1,260	1,260	725	249	4,866		1.386	0.047	920	19,330	83.3	14,850
145	110	110	64	429	19.4	409.6	1,596	1,260	1,260	725	265	5,106	12,370	1.422	0.047	1,020	19,980	82.7	15,070
160	110	110	64	444	20.1	423.9	1,768	1,260	1,260	725	281	5,294		1.455	0.047	1,100	20,570	82.1	15,210
160	110	110	64	444	20.1	423.9	1,768	1,260	1,260	725	281	5,294		1.455	0.047	1,100	21,500	82.1	15,210
160	110	110	70	450	20.4	429.6	1,768	1,260	1,260	806	288	5,382	12,980	1.472	0.047	1,150	21,830	81.8	15,320
160	110	110	80	460	20.8	439.2	1,768	1,260	1,260	933	300	5,521		1.500	0.047	1,260	22,410	81.4	15,440

3. Compute and plot the average incremental rate curve corresponding to the average input-output curve of (2). On the incremental rate curve indicate the loads at which it is proper to add additional units.

4. Divide the system load on the basis of the average incremental rate curves of (3). The station loads so determined will indicate the combination of units that should be operated at each station.

5. Redivide the system load using the actual incremental rate curves that correspond to the combinations determined under (4).

Conclusion

In reading this paper one may get the impression that the application of incremental rates to load division is very complicated and difficult. The question arises "Are the savings that can be effected worth the effort?"

It certainly is apparent that in the larger stations of recent design with highly efficient units available, it will be advantageous to study the loading sequence carefully in order to maintain the operating procedure at its highest efficiency. In these stations a small gain in efficiency will result in savings of considerable magnitude, due to their large outputs. In addition to the gains effected by accurate load division, there are benefits to be derived from having available accurate performance data on the individual equipment, permitting the calculation of a reliable "bogey" performance, which, compared with the actual performance, will direct the attention of the operating personnel to any faulty performance.

In the case of stations of the older type, with relatively lower operating efficiencies, the careful analysis of operating procedure for the purpose of establishing the incremental rates, may lead to changes in practice which will result in savings of the same magnitude as those effected by a change in load division.

Application of the principles of incremental rate loading, based upon careful analysis of operating conditions, gives assurance that equipment of the system is being utilized to the best advantage. It also has the valuable effect of keeping the operating personnel on the alert to maintain the most efficient operation.

Appendix A

(See p. 445, March 1934 issue of ELECTRICAL ENGINEERING.)

Appendix B

PROOF THAT INDEPENDENT LOADING OF BOILERS AND TURBINES INCREMENTALLY WILL RESULT IN MAXIMUM STATION EFFICIENCY

Consider 2 boilers operating with 2 turbines; the characteristics of the boilers and of the turbines are different. Either turbine may be partially or wholly supplied from either boiler. With both boilers and both turbines on the line, let

L = total station load
L_1 = load on turbine No. 1
L_2 = load on turbine No. 2
T_1 = heat input to turbine No. 1
T_2 = heat input to turbine No. 2
O_t = total heat output of boilers
O_1 = heat output of boiler No. 1
H = heat output of boiler No. 1 not used in turbine No. 1
O_2 = heat output of boiler No. 2
I_1 = heat input to boiler No. 1
I_2 = heat input to boiler No. 2
I_t = total heat input to both boilers

T_1 and T_2 include the respective turbine auxiliaries. I_1 and I_2 are the inputs necessary to furnish O_1 and O_2 plus the respective boiler auxiliaries. All auxiliaries are steam driven. Then

$$L = L_1 + L_2$$

$$T_1 + T_2 = O_t = O_1 + O_2$$

$$T_1 + H = O\,; \quad T_2 - H = O_2$$

and

$$I_t = I_1 + I_2$$

Suppose L_1 and O_1 are chosen as the 2 independent variables. The problem is to determine, for any total load L, the values of L_1 and O_1 which will give the minimum station input. Let us assume that the boiler and turbine input-output curves are all continuous and that the respective incremental rates never decrease as the output increases.

The condition for a minimum is expressed mathematically by the equation

$$dI_t = 0 \qquad (1)$$

But

$$dI_t = \frac{\partial I_t}{\partial L_1}\,dL_1 + \frac{\partial I_t}{dO_1}\,dO_1 \qquad (2)$$

Since L_1 and O_1 are independent variables, it is necessary that

$$\frac{\partial I_t}{\partial L_1} = 0 \quad \text{and} \quad \frac{\partial I_t}{\partial O_1} = 0 \qquad (3)$$

in order that dI_t shall vanish. But

$$\frac{\partial I_t}{\partial O_1} = \frac{\partial(I_1 + I_2)}{\partial O_1} = \frac{\partial I_1}{\partial O_1} + \frac{\partial I_2}{\partial O_2} \times \frac{\partial O_2}{\partial O_1}$$

Also

$$O_2 = O_t - O_1$$

and

$$\frac{\partial O_2}{\partial O_1} = \frac{\partial O_t}{\partial O_1} - \frac{\partial O_1}{\partial O_1} = -1$$

Since O_t is independent of O_1. Hence

$$\frac{\partial\ _t}{\partial O_1} = \frac{\partial I_1}{\partial O_1} - \frac{\partial I_2}{\partial O_2} = 0$$

or

$$\frac{\partial I_1}{\partial O_1} = \frac{\partial I_2}{\partial O_2} \qquad (4)$$

This simply means that the boiler incremental rates are equal. Similarly

$$\frac{\partial I_t}{\partial L_1} = \frac{\partial I_1}{\partial L_1} + \frac{\partial I_2}{\partial L_2} \times \frac{\partial L_2}{\partial L_1}$$

$$= \frac{\partial I_1}{\partial O_1} \times \frac{\partial O_1}{\partial L_1} + \frac{\partial I_2}{\partial O_2} \times \frac{\partial O_2}{\partial L_2} \times \frac{\partial L_2}{\partial L_1}$$

Also

$$\frac{\partial L_2}{\partial L_1} = \frac{\partial(L - L_1)}{\partial L_1} = -1$$

Now, since

$$\frac{\partial I_t}{\partial L_1} = 0 \qquad (3)$$

$$\frac{\partial I_1}{\partial O_1} \times \frac{\partial O_1}{\partial L_1} = \frac{\partial I_2}{\partial O_2} \times \frac{\partial O_2}{\partial L_2} \qquad (5)$$

But

$$\frac{\partial I_1}{\partial O_1} = \frac{\partial I_2}{\partial O_2} \qquad (4)$$

ence eq 5 reduces to

$$\frac{O_1}{L_1} = \frac{\partial O_2}{\partial L_2} \tag{6}$$

urthermore $O_1 = T_1 + H, \quad O_2 = T_2 - H$

$$\frac{O_1}{L_1} = \frac{\partial T_1}{\partial L_1} + \frac{\partial H}{\partial L_1} \tag{7}$$

nd

$$\frac{O_2}{L_2} = \frac{\partial T_2}{\partial L_2} - \frac{\partial H}{\partial L_2} = \frac{\partial T_2}{\partial L_2} - \frac{\partial H}{\partial L_1} \times \frac{\partial L_1}{\partial L_2} = \frac{\partial T_2}{\partial L_2} + \frac{\partial H}{\partial L_1} \tag{8}$$

ubstituting eq 7 and eq 8 in eq 6

$$\frac{T_1}{L_1} = \frac{\partial T_2}{\partial L_2}. \tag{9}$$

ut $\frac{\partial T_1}{\partial L_1}$ and $\frac{\partial T_2}{\partial L_2}$ are the incremental heat rates of turbines num- er 1 and number 2, respectively. Hence, the requirements for a inimum station input, as shown by eqs 4 and 9, are to operate ı) the 2 boilers at the same incremental rates, and (*b*) the 2 turbines t the same incremental rates, respectively. It has already been nown that conditions (*a*) and (*b*) are those which result in minimum oiler room and minimum turbine room inputs, respectively.

ffect of Steam Tie Line of Limited Capacity

When there is a tie line of limited capacity between boilers num- er 1 and number 2, it may no longer be possible to assume that $_1$ and O_1 are independent variables. Assume that the maximum eat that can be transferred through the tie line is H_0. As long as ne difference between O_1 and T_1 is less than H_0 the turbines and oilers can be loaded independently. When the transfer through ne tie reaches H_0 eqs 4 and 6 no longer hold. There is only one ndependent variable, say L_1. Equation 1 becomes

$$\frac{I_t}{L_1} = 0 \tag{10}$$

$$= \frac{dI_1}{dL_1} + \frac{dI_2}{dL_2} \times \frac{dL_2}{dL_1}$$

$$= \frac{dI_1}{dL_1} - \frac{dI_2}{dL_2}$$

r

$$\frac{I_1}{L_1} = \frac{dI_2}{dL_2} \tag{11}$$

nd

$$\frac{I_t}{O_1} \times \frac{dO_1}{dL_1} = \frac{dI_2}{dO_2} \times \frac{dO_2}{dL_2} \tag{12}$$

ut since

$_1 = T_1 + H_0$

nd $O_2 = T_2 - H_0$

nd H_0 is a constant it follows that

$$\frac{O_1}{L_1} = \frac{dT_1}{dL_1}$$

nd

$$\frac{O_2}{L_2} = \frac{dT_2}{dL_2}$$

ence

$$\frac{I_1}{O_1} \times \frac{dT_1}{dL_1} = \frac{dI_2}{dO_2} \times \frac{dT_2}{dL_2} \tag{13}$$

his simply means that the over-all incremental heat rate of turbine nd boiler number 1 which is the product of their respective incre- ental rates, shall equal the over-all incremental heat rate of turbine nd boiler number 2. It will be noted that if one boiler is operated at higher pressure than the other, the quantity H could not be nega- ve, but would have to lie between zero and H_0.

The extension of the above analysis for more than 2 boilers or turbines will not be included here. The same conclusion will be reached, namely, that all of the boilers and all of the turbines, respectively, should be operated at equal incremental rates. When this is not possible, the combined boiler and turbine incremental rates of the several groups should be kept equal.

Appendix C

Derivation of Equation for Station Incremental Rate in Terms of Incremental Rates of Boilers, Turbine-Generators and Auxiliaries

In Fig. 30 are shown the performance curves of the station equipment for a given combination of boilers and turbines. Assuming that the boilers and turbines independently are loaded incrementally, and that the station performance represents continuous functions whose incremental rates are nondecreasing, let

I_T = total station input
O_T = total boiler output
T = total turbine input
S = heat input to steam auxiliaries
E = power consumption of the electric auxiliaries
L = gross station load (total generator load)
L_N = net station load

Then

$O_T = T + S$

$L_N = L - E$

$$\frac{dI_T}{dL_N} = \frac{dI_T}{dO_T} \times \frac{d(T+S)}{dL} \times \frac{dL}{d(L-E)}$$

$$= \frac{dI_T}{dO_T} \times \left[\frac{dT}{dL} + \frac{dS}{dL}\right] \times \frac{1}{1 - \frac{dE}{dL}}$$

Let

$$\frac{dI_T}{dO_T} = R_B; \quad \frac{dS}{dL} = R_S; \quad \frac{dT}{dL} = R_T; \quad \frac{dE}{dL} = R_E; \quad \frac{dI_T}{dL_N} = R_{ST}$$

Hence

$$R_{ST} = \frac{R_B(R_T + R_S)}{1 - R_E}$$

Where

R_{ST} = station net incremental rate
R_B = boiler incremental rate
R_T = turbine incremental rate
R_S = incremental rate of steam auxiliaries
R_E = incremental rate of electric auxiliaries

Appendix D

Derivation of Equation for Load Division Between Stations Joined by a Transmission Line

When 2 generating stations are joined by a transmission line, correct load division must take into account the losses of the line when under load.

Let the subscripts s and r designate the sending and receiving ends of the transmission line, respectively. Then let

L_s and L_r = loads in the areas served by the respective generating stations (constants)
G_s and G_r = loads generated by the stations
I_s and I_r = inputs to the generating stations corresponding respectively to G_s and G_r
I_t = combined input to both generating stations
T_s and T_r = loads on the transmission line at the sending and receiving ends, respectively

R_s and R_r = station incremental rates corresponding respectively to the loads G_s and G_r

E_t = absolute efficiency of the transmission line

E_{it} = incremental efficiency of the transmission line $= \dfrac{dT_r}{dT_s}$

I_s, I_r, T_s, and T_r are assumed to be continuous functions with never-decreasing incremental rates. Then

$$I_t = I_s + I_r \qquad G_r = L_r - T_r$$

$$G_s = L_s + T_s \qquad T_r = T_s \times E_t$$

Let G_s be the independent variable. The conditions for minimum combined input to the 2 stations will then be

$$\frac{dI_t}{dG_s} = 0 \quad \text{or} \quad \frac{dI_s}{dG_s} + \frac{dI_r}{dG_s} = \frac{dI_s}{dG_s} + \frac{dI_r}{dG_r} \times \frac{dG_r}{dG_s} = 0$$

But $\dfrac{dI_s}{dG_s} = R_s$; $\dfrac{dI_r}{dG_r} = R_r$ and

$$\frac{dG_r}{dG_s} = \frac{d(L_r - T_r)}{d(L_s + T_s)} = -\frac{dT_r}{dT_s} = -E_{it} \quad \text{since } L_s \text{ and } L_r \text{ are constants.}$$

Hence $R_s - R_r \times E_{it} = 0$ or $R_s = R_r \times E_{it}$

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Flying 60 Tons of Machinery Into the Peruvian Andes

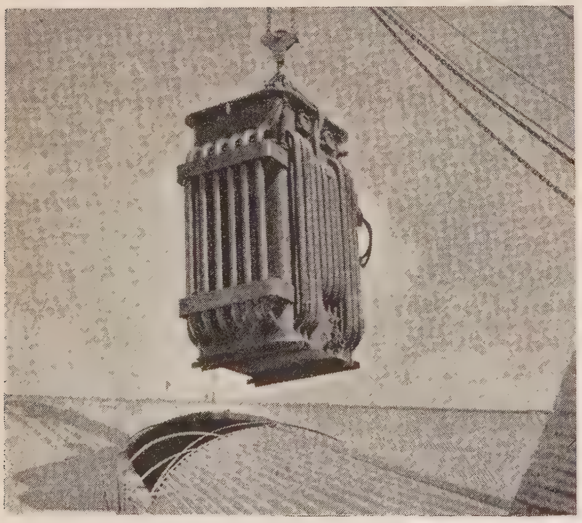


Photo Courtesy, the *Compressed Air Magazine*

Four hundred years ago the already-ancient Ccochasayhuas gold mine was discovered by the Spaniards about 60 miles from Cuzco, the ancient capital of the Incas. Today, this mine is producing gold, and under the influence of modern methods, its production is being increased. Since 1930, much modern equipment has been installed, and a hydroelectric plant has been built. No means of getting the equipment over the mountains and rugged country was possible except that of transportation by air, and accordingly, after some experimental work the 60 tons of freight was carried by plane from Cuzco to the mine. The plane averaged 4 round trips daily, and the entire consignment of 60 tons was transported in 12 days. Some of the heavier pieces, such as the transformer shown in the illustration, weighed as much as 2,000 lb, and were transported without difficulty. On most of the trips the total load carried was about 3,000 lb. The Ccochasayhuas mine is at an altitude of about 15,000 ft, and the hydroelectric plant, a few miles away, is at an elevation of about 13,000 ft. The ultimate capacity of this plant is 2,250 hp, of which 2 750-hp generating units were installed last year.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON this and the following pages appear those discussions of A.I.E.E. winter convention papers that were received in complete and acceptable form at Institute headquarters between February 5 and March 1, 1934, and subsequently reviewed by the various technical committees, and recommended for publication. Discussions received up to February 5, and recommended for publication by the various technical committees previous to the time of going to press of the March 1934 issue, were published therein, p. 446–95. These 2 groups will no doubt account for the bulk of the total discussion of the winter convention papers as published in the August, November, and December 1933, and January 1934 issues. However, discussions which may be received in the future will be given the same attention as those received previously, and will be judged on the same basis for possible publication.

For the majority of papers, authors' formal closures are included in the present issue. Wherever closures have been submitted, they appear at the end of the discussion for the paper. They embrace all discussions received and accepted by March 1.

THIS new department inaugurated with the March 1934 issue of ELECTRICAL ENGINEERING marks a further step in the evolution of the unified publication plan adopted by the A.I.E.E. board of directors in August 1933, the purpose of which is to carry to every member of the Institute all technical and related material as promptly as it can be released and published. Another wish is to stimulate and facilitate a broader participation on the part of Institute members everywhere in the study and discussion of current technical papers. Therefore, members anywhere are encouraged to submit written discussion of any A.I.E.E. paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions should be: (1) concise; (2) restricted to the subject of the paper or papers under consideration; (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, headquarters of the American Institute of Electrical Engineers, 33 West 39th Street, New York, N. Y.

Switching at the Hudson Avenue Station

Discussion of a paper by C. M. Gilt published in the December 1933 issue, p. 868–75, and presented for oral discussion at the electric power switching discussion of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

C. M. Gilt: Some of the discussions of the papers on generating station switching have suggested a little disappointment at the lack of evidence of uniformity or standardization in design. To me it was somewhat surprising that the system conditions in Detroit and Brooklyn are near enough alike so that the switching at Conners Creek and at Hudson Avenue are both built around a very similar one line diagram and use a similar principle of segregation, although equipment and materials differ. Standardization of generating station design would involve most of the evils of the process and few of its benefits. In general, standardization is a compromise design endured to secure the advantages of interchangeability or lower cost made possible by using special automatic machines in fabrication and mass production. Certainly no stretch of the imagination could attribute any great advantages to general interchangeability between generating stations, or anticipate mass production of them. One would lose a great deal in trying to fit a common station design or equipment to a station like Hudson Avenue, built within a city, close to its load center, itself forming a distributing point, to a station like Long Beach No. 3 which is one of several stations feeding onto a double 220-kv bus over 250 miles long, and to one like State Line which delivers bulk power over and ties together a number of high capacity lines of three different voltages. There is real justification for differences in design of stations even when feeding load under what superficially appears to be similar conditions, as such things as past experiences, training of personnel and existing commitments may be enough to throw the balance of advantages and disadvantages one way or another. Such being the case, it is doubtful that the suggestion of Mr. Hollister that generating stations be divorced from "subtransmission" switching substations should apply in all cases, but rather the economics of all the local factors should govern.

The development of switchgear and bus insulation without oil or inflammable fluids is highly commendable and should be encouraged. While the oilless Deion breakers have been developed, they were not available for 27,000-volt operation when the last switchgear was purchased for Hudson Avenue. Had it been available, I am confident that at least a trial installation would have been made.

While Mr. Sanderson points out that there have been some troubles with disconnecting type of contacts, such as are used on elevating or draw out type of breakers, it should be pointed out that this type of installation was made with the primary purpose of avoiding the disastrous experiences which have occurred all too frequently when a disconnecting switch that was carrying load is opened manually. There have been no troubles with the disconnecting contacts of the elevating breakers at Hudson Avenue. I have no doubt that this is in part due to the fact that the elevating mechanisms are integral with each breaker and therefore insure proper alignment and travel of the contacts when closing. This is somewhat more difficult to obtain when a common, portable elevating platform is used for all breakers.

The question of generator voltage is largely one of economics. If, as Mr. Hollister suggests, the tendency toward high voltage switching at, and transmission from generating stations increases, the urge for higher voltage generators is somewhat reduced, as these higher voltages are commonly beyond the possibilities of direct generation. Higher voltage generation was flirted with throughout the development of Hudson Avenue. The specifications for the last two units were written to give the manufacturers a free hand in designing the best combination of generator and autotransformer, or generator alone, to give 27,600 volts. Loss evaluations were given, and higher voltage generation was encouraged to the extent that the high voltage test specified was reduced somewhat relative to the generator voltage, as the generator voltage was increased, so as to reduce the corona difficulties during test. The most economical overall combination proved to be 16,500-volt generators with autotrans-

formers stepping up to 27,600 volts.

The size of generator selected for a station must be determined by over-all economics and an arbitrary upper limit within manufacturing limits can hardly be set. The size of machine is affected by rate of load growth as well as size of load. Some studies I made a few years ago indicate that one can frequently secure lower cost firm capacity by using relatively few large units even though this results in some excess in total kw capacity installed as compared with the use of smaller machines, and furthermore, this excess capacity soon becomes usable capacity in a growing system.

I am entirely in sympathy with Mr. Sporn's objective of having Institute papers that give reasons for doing things rather than simply a description of what has been done. In reviewing my own paper I find that the explanations are not as clearly pointed out, and particularly the reasons back of the principles which are indicated as being controlling factors are not as well given as I intended in writing the paper. However, an author is limited by the very practical consideration of space and the reader's patience, and the further difficulty of being able to distinguish between a rationalization of what has been done and the real motivating factors that governed when the design was prepared.

Switching at Richmond Station

Discussion of a paper by Raymond Bailey and F. R. Ford, published in the January 1934 issue, p. 156–61, and presented for oral discussion at the electric power switching discussion of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

F. R. Ford: With regard to Mr. Hall's statement that he questions the wisdom of installing very large generating units, it might be stated that the economic necessity for utilizing available sites to the fullest extent to secure the lowest possible unit costs per kw justified the selection of the 165,000-kw generator which is being installed at Richmond Station, as this is the largest unit which can be installed in the space available in the existing building. The desirability of using the Richmond site to the fullest advantage is also emphasized by the high cost of new sites for steam plants in or adjacent to Philadelphia.

The new unit will operate on a high capacity interconnection aggregating approximately 2,000,000 kw in generating capacity. The size of new units is determined largely by conditions on the interconnection rather than local conditions in the individual systems interconnected. Although the new unit represents a substantial portion of the Philadelphia Electric Co. generating capacity of approximately 950,000 kw, the high rating is justified by the magnitude of the interconnection which is operated, as nearly as practicable, as would be done if all the companies participating were under one management.

Analyses which have been made indicate that no difficulty need be anticipated with regard to division of load between the 2 windings of the 165,000-kw unit or control of their respective power factors. The unit will normally feed one end of the reactor sectionalized 13.8-kv bus with the 2 windings directly in parallel. With regard to control of load on the bus, this will be facilitated to a considerable degree by a certain flexibility in the use of the 43,000-kva frequency converter sets in the adjacent substation and by the 60,000-kva 13.8/69-kv bus tie transformer banks, as one of each of these equipments is connected to each end of the bus.

Mr. Sporn believes the papers should give more discussion of the fundamental principles underlying the designs of the various plants described. Reference to the discussion by Mr. Lovell summarizing the reason for the papers and the essential features of each will indicate that it was intended primarily to bring out the trends of the latest designs and the limitations and operating experience realized under actual working conditions. On this basis, only sufficient description was given of the Richmond Station to form a background against which the detailed operating experience could adequately be given. Accordingly, no attempt was made to discuss the underlying features of the design, such as the double bus arrangement and the "H" connection of the 13.8-kv line pairs as it was assumed that the relative advantages and disadvantages of such arrangements as have been common for many years are well known at the present time. It was believed that the major point of interest with regard to Richmond Station, at least, was the experience which has been realized with the existing design rather than to elaborate on the design principles involved in the station, the construction of which was started ten years ago. No doubt some of the principles which were felt to be important at that time would be viewed somewhat differently today in developing a new generating station.

Switching at the Connors Creek Plant

Discussion of a paper by A. P. Fugill published in the January 1934 issue, p. 162–8, and presented for oral discussion at the electric power switching discussion of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

A. P. Fugill: Although most of the discussion on the paper on the Essex Station of the Connors Creek Plant requires no further comment on the part of the author, a few of the points mentioned might be discussed briefly.

Since Essex has been in service only a short time, there seems to be some doubt as to whether its present good operating record will continue over a period of years. Time only will answer that question but, as mentioned in the paper, there are four other stations on the Detroit Edison system using the same general arrangement and practically identical equipment, particularly the insulated metal housings and bus fault protection. The oldest of these has been in service for $5^1/_2$ years and the most recent for 3 years, and to date no major trouble has occurred.

In speaking of the possible future trend toward unit operation of generator and step-up transformer with transmission to load centers at some higher voltage, F. H. Hollister mentioned Trenton Channel as one of the earlier examples of this scheme but stated that this station uses low tension switching. Actually the low tension switching consists merely of a series breaker and disconnects between each generator and transformer. They were installed principally to provide trip-free operation in case of closure on a fault and to facilitate synchronizing.

The use of higher voltage generators was mentioned in several discussions. This question was considered very carefully in connection with the rehabilitation of Connors Creek and the design of Essex. In this particular instance, since some reactance in series with the generator was needed to meet fault current limitation requirements, the inherent reactance of the auto-transformer eliminated the use of a series reactor. Considering this factor and the present greater cost of higher voltage generators, it was found that the most economical combination was a 14.4-kv generator with an autotransformer to step up to 24 kv, compared to the 12 kv generator used at other plants on the system.

H. Y. Hall points out that ground connections to insulated housings must be carefully made to prevent hazard to operators. Most assuredly, the voltage between the housing and the point where the operator may be standing must be kept to a safe value during fault conditions. To accomplish this most effectively, the impedance of the connection from the housing to the ground bus must be low and the building steel should be thoroughly connected to the same ground bus. Incidentally the reactance of the ground connection is even more important than the resistance. In designing Essex, the desired result was accomplished by using a grid for the ground bus instead of a single bar, tying the building steel to the grid at frequent intervals, and then making the connection between the metal housing and the ground grid as short as possible. Of course, all the ground bus in the station was solidly connected to a low impedance distributed ground mass outside the building.

Mr. Hall is correct in stating that both system interconnections to Essex are made to the equalizer bus. If this bus has an emergency shutdown, the system ties are lost, but the system operation is such that the station can carry its local load until relief is provided. In addition, readily removable links are provided at 2 points in the bus so that any third of the bus can be cut out in a short time and the rest of the bus put back into service. No bus trouble should cause a loss of both system ties for more than about half an hour.

J. K. Ostrander compares the protective scheme for bus faults such as used at Essex with bus differential protection. The Detroit Edison uses both schemes, the former

on indoor stations where positive housing insulation is easily obtained, and the latter on outdoor stations where the insulation of the equipment structures present a rather difficult problem. There are most certainly applications for both types of bus fault protection, but, in indoor stations at least, our experience indicates that there are fewer complications in a new station in applying this insulated metal housing scheme than the bus differential method. It is doubtful if any differential scheme can be devised which is as simple, reliable and positive as the type of bus fault protection used at Essex.

C. H. Sanderson suggests that the armored control cable should prove cheaper in cost and maintenance or extension than the conventional rigid conduit installation. On the latter points no information is available but the actual cost of the armored control cable installation at Essex was 30 per cent less than comparable rigid conduit installations at other stations on the system.

The Pitt-Westinghouse Graduate Program

Discussion of a paper by H. E. Dyche and R. E. Hellmund published in the January 1934 issue, p. 103–8, and presented for oral discussion at the education session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 44–9.

C. L. Dawes: In his summary of the program of the Engineers' Council for Professional Development, Dean Barker states that one phase of the program is to stimulate self-education and initiative among the young engineering graduates. Also in the paper by Professor Dyche and R. E. Hellmund, it is stated that "no matter how carefully the curriculum may be planned and how thoroughly the college work carried out, it will have to be admitted that it is at best very difficult to give to the student in a purely university atmosphere that training in developing initiative, resourcefulness, action, and responsibility which is required in actual practice."

Both statements emphasize the lack of initiative in our engineering graduates. Also, of the many criticisms of engineering graduates which I hear from time to time, lack of initiative is the most frequent, and, from personal experience, I feel that there is some justification for it.

I believe that this lack of initiative is due in large measure to the fact that the methods of teaching employed as a rule in our engineering schools, and through our general educational system as well, actually suppress and stifle initiative and resourcefulness. In the lower schools the program of study, the hours devoted to different subjects, even the methods of holding a pen or pencil, are all standardized. In the preparatory schools this same procedure is followed. In the preparation for entrance into higher institutions of learning it is required that definite numbers of hours be devoted to English, mathematics, science, language, history, etc. The student is not given the reasons why the prescribed system of studies best adapts him to the higher education of the college. There probably are none.

In the engineering school the same general process is continued. Curricula have been carefully developed and proportioned. Presumably the proportions of mathematics, sciences, languages, economics, and engineering which will best train all individuals to be good engineers have been determined. The student follows the prescribed curriculum without questioning its purpose, and he knows that if he is at all successful in passing the individual courses he will be given a degree. This may explain in part the fact stated by Messrs. Dyche and Hellmund that the most carefully planned curriculum fails to develop initiative, resourcefulness, and responsibility.

The same tendency to discourage initiative exists in the courses of instruction; the student is given definite assignments to be carried out at definite times; he is assigned definite laboratory experiments to be performed at definite times and the procedure in performing the experiment is usually carefully prescribed.

It is little wonder that after graduation he fails to continue his education, and fails to develop initiative. There is no one to tell him what to study, where to study, when to study, and to assign him experimental work with detailed directions for performing it.

At the graduate school of engineering at Harvard we have attempted to adjust our educational methods so that resourcefulness and initiative are at least encouraged. There is no fixed curriculum. The responsibility for arranging his curriculum is placed on the student. It is required merely that the program be substantial and that it show a definite purpose.

In general, the class-room work consists of informal discussions rather than of formal lectures. Courses terminate in a 3-weeks' reading period during which there is no class-room work, and the student completes the course entirely on his own responsibility. The laboratory work consists of a few projects more or less optional, rather than definite laboratory experiments to be performed at a definite time and in a prescribed manner.

These methods of placing responsibility directly on the student and minimizing supervision may not entirely solve the problem, but certainly they do encourage initiative and resourcefulness. The results confirm our belief that this is true.

The statement in the paper, "There is a distinct danger in extending the engineering college course beyond the usual 4-year program, except for those who expect to make research or teaching their life work," I believe is contrary to the facts. Innumerable instances could be cited of outstanding engineers whose technical education in the engineering college has extended into 1 year and more beyond the usual 4-year course. In fact, at the present time a strong sentiment exists among engineering teachers and in industry as well that the 4-year course in an engineering school is entirely inadequate preparation for an engineering career. (An excellent discussion of this subject is given in a paper "The Five-Year Engineering Course," by W. S. Rodman, presented before the engineering section of the convention of the Association of Land-Grant Colleges and Universities in Chicago, Nov. 13, 1933.) It is my opinion that extension of the 4-year engineering course one or more years is not a danger, but will soon become a necessity in the preparation of engineering students to meet the complex conditions of modern civilization.

The coöperative Westinghouse program described in the paper does develop without doubt a high-grade graduate school, particularly when the requirements for the degree are maintained on the high plane stated in the paper. Some of the graduates whose names appear under "completed theses" bear witness to this fact. However, it must be remembered that relatively few engineering schools are so situated that coöperation with a large industry is possible. It is true, nevertheless, that many such schools can and do maintain a high type of graduate work. Nor are facilities for an advanced type of research entirely lacking. It is significant that many large industries and engineering associations send their research problems to the research laboratories of the engineering schools for development and solution. I know from personal experience that the facilities for certain types of research are greater in some of our engineering schools than in some industrial research laboratories. On numerous occasions the Harvard Engineering School has loaned equipment to such industrial laboratories. It is true that graduate work, particularly of the most advanced type, should be limited to the institutions having the greatest resources. The S.P.E.E. board of investigation and coördination also came to this conclusion. The following statement is found in its report (v. 1, 1928–29, p. 117): "It is desirable that resident graduate work should be undertaken only by engineering colleges with notable teachers and exceptional facilities; ..."

The graduate program described in the paper by Messrs. Dyche and Hellmund is well adapted to conditions in which a large industry is located in close proximity to an engineering school and offers stimulation and excellent facilities to young engineers employed in the industry. I believe, however, that schools not so located will continue to develop graduate students with initiative and resourcefulness, particularly if they employ methods of teaching which place a large measure of responsibility on the individual student.

W. M. Young: While teaching at the Texas Technological College at Lubbock, Texas, the problem of supplementing a man's collegiate education, after he had assumed a position in industry and was connected with a company at a relatively large distance from the college, was frequently brought to mind and the subject was given only general consideration. At that time, no advanced degrees were offered in engineering, and the whole attention of the teaching staff was occupied in establishing a sound engineering school. However, it was then realized that ultimately an educational institution must offer means for professional advancement to men distantly located.

The papers presented this morning and the discussion, in the main, have centered about the problem of supplementing a man's education when the industry and college

were located either in the same town or relatively close together. The solution of this problem as presented by the Westinghouse-Pitt agreement and the M.I.T.-General Electric arrangement has been very interesting.

There remains, however, a much larger problem for consideration. At the present time, we, at the Taylor Instrument Companies, are interested in securing men to fill certain vacancies. We have generally chosen the engineer in preference to the physicist, largely because his fund of information was general and his mode of thinking analytical. The men must then be given additional training in the different departments of the plant to fit them for service in our particular fields of endeavor—temperature and pressure indication and control. At various times, members of different departments have expressed a desire to improve their store of knowledge and have done so through the medium of individual reading, but no means are readily available whereby an employee may obtain an advanced degree through the completion of the necessary courses and thesis.

It frequently happens that small industrial organizations have not only the facilities for conducting research problems but also have men capable of directing these problems. In such instances, it is particularly desirable that members of such organizations have means whereby they can secure advanced degrees through the coöperation of a university or college granting such degrees. When these smaller organizations are located at a relatively large distance from a suitable educational institution, the problem assumes real proportions and up to the present time no satisfactory arrangements are known.

It is suggested, therefore, that the education committee of the Institute give very serious consideration to the problem of offering professional advancement and advanced degrees to men in industry, and to the organization of means whereby this can be accomplished when the industrial organization is small and is located at a relatively large distance from the educational institution.

D. C. Jackson, Jr.: The trend among the majority of industries and utilities because of present business conditions seems to be to continue with a week reduced in length to about 5 days. This is a challenge to the engineering schools to make available to the completest degree for their alumni and for the alumni of sister institutions their facilities for graduate study. By adjustment of schedules, it is possible to place on Fridays and Saturdays those purely graduate courses which are of interest to the engineering alumni in the vicinity. In the case of engineering schools located in cities this is not so necessary, but where an engineering school is situated as many state universities are, in a relatively small city some distance from any large industrial center, such graduate instruction can be carried on only when the practicing engineers interested can have a couple of days in succession free from their regular employment.

The University of Pittsburgh and the Westinghouse Electric and Manufacturing Company have accomplished very worth while and laudable results in their program. Other engineering schools located in industrial centers have also been successful in arranging graduate work for practicing engineers in their vicinity. However, it seems desirable to encourage not merely the engineering schools, but also the abler of our more recent engineering alumni to undertake some such coöperative scheme, especially in those parts of the country where the industrial centers may be at some little distance from the nearest engineering school.

R. E. Hellmund: In closing the discussion of our paper, I should like to call attention to the very general agreement among those who discussed the paper on the broad fundamentals expressed in it. It should also be noted that there is a rather surprising accord between the principles set forth in Dean Barker's excellent report on the activities of the Engineers' Council for Professional Development, which deals to a large extent with postgraduate educational matters, and the fundamental ideas covered in our paper.

As a matter of course, the manner in which these ideas are carried out will have to be governed by local conditions and existing opportunities. In the discussion we have heard of the postgraduate plan carried on in coöperation with the Lynn works of the General Electric Company. This plan apparently is somewhat similar to the University of Pittsburgh-Westinghouse program because the existing conditions are somewhat the same. As pointed out in some of the discussions, however, conditions in the South and West are not so favorable as in the large industrial centers. It is very important that attempts be made to create similar opportunities for graduate students in these sections in keeping with the conditions found there and, in fact, in any cases where the industries are located in places remote from educational institutions. But in the meantime every advantage possible should be taken of the more favorable conditions in the East. Incidentally, the University of Pittsburgh-Westinghouse plan is carried on at the Sharon plant, at a distance of 80 miles from the University, by weekly trips of faculty members to Sharon.

I was very much interested in the efforts made in the St. Louis territory to carry on postgraduate programs for the benefit of the engineers of the local industries. It is to be regretted that such worthy attempts failed largely on account of the financial sacrifice necessary on the part of the students. This is a matter which should be given very careful consideration, because even with the relatively low cost of the University of Pittsburgh-Westinghouse program, quite a number of the students failed to complete their work because of the financial burden it entailed. It must be realized that graduates at that age frequently are in the early period of married life and consequently have many demands upon their very limited financial resources. It is therefore most essential that whatever programs are arranged take this into account.

Appendix II may be somewhat misleading to readers in that it seems to indicate a preponderance of engineering subjects in the postgraduate program. Attention might therefore again be called to the fact that the appendix lists only the courses covered by the Westinghouse lecturers, this being done largely for the purpose of indicating the type of material covered by them. As stated in the paper, at least 10 credits must be obtained through courses given by the regular staff of the University, but it would, of course, be impossible to cover in the paper the very extensive list of subjects available for this purpose. The courses given by the University faculty relate as a rule to mathematics, physics, psychology, economics, etc., and these courses together with those given by the Westinghouse lecturers represent a very well balanced postgraduate program for engineers. As stated in the discussion, it is rather difficult to get a clear picture from Appendix I of the actual material covered by the theses. However, with the subjects available in the appendix, it is possible for anybody interested to obtain abstracts of the theses from the University.

Attention may be called to another point, namely, what appears to be an inconsistency between the statement made in the paper to the effect that a reasonably large percentage of graduate students should be able to obtain additional degrees and the fact that the engineers who have taken the Pitt-Westinghouse course represent a highly selective group and that only a small percentage even of those have obtained degrees. In this connection it will have to be admitted that so far the University has proceeded rather cautiously in conferring degrees. Nevertheless, I personally feel that the various postgraduate coöperative programs should eventually be so arranged that about 20 to 30 per cent of the engineering profession can obtain additional degrees.

One criticism offered to the ideas expressed in the paper is that with regard to the statement that there is danger in spending more than 4 consecutive years in college. From my experience with a great many graduate students, I am firmly convinced that this statement in the paper is correct, but this does not mean that courses extending over a period of more than 4 years are necessarily wrong. The success of these longer courses depends entirely upon the extent to which they recognize the fundamentals of engineering education and carry on the work accordingly. When I say recognize the "fundamentals," I do not mean the usual fundamental knowledge to be acquired during the college course, but rather the recognition of the basic fact that the engineering profession is a profession of creating and that it is therefore essential that any engineering education to be effective must develop in the student not only the desire and ability to create, but also the habit of doing so. This fundamental should be given recognition beginning with the freshman year. Although, as often pointed out by the industries, they do not expect from the colleges engineers fully trained in designing or engineering any particular piece of apparatus, they do expect graduates to display evidence that their ability for creative work of some kind has been cultivated and stimulated. I do not think that the fact that college curriculums are already overcrowded is any excuse for neglecting this phase of engineering education. As a matter of fact, some of the discussions indicate that some schools are making definite

efforts along this line, which is very encouraging.

In this connection, actual experience with the Pitt-Westinghouse program should prove very illuminating because it bears out the above statements. Before the institution of the Pitt-Westinghouse program, the Westinghouse company carried on extensive educational courses. As a rule, many of the better students did not appear to be very eager to take up this work as they were anxious to try out in actual practice the knowledge acquired at school, a spirit which is highly commendable. I therefore felt that when the Pitt-Westinghouse program was started, requiring about 10 additional credits to be acquired at the University in such subjects as mathematics, physics, etc., the students' reaction would not be very favorable. However, it developed that in view of the fact that the habit of studying had been well fixed in them, they peacefully knuckled down to this additional study; but when it came to preparing a thesis, which of course required originality and initiative, the large majority of them exhibited a certain helplessness and this work seemed to be the main stumbling block in the course for the master's degree. To me, this was simply an indication that their college work had failed to develop them sufficiently along these lines.

Pantograph Trolleys I—Design Features

Discussion of a paper by W. Schaake published in the January 1934 issue, p. 182–9, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 451.

W. Schaake: In Harry Brown's discussion his reference to the cambered shoe used by New Haven gives good reasons for the use of this type of shoe. The objection which I have to this form of shoe is due to the fact that the point of contact with the contact wire is over 2 in. above the fulcrum point of the shoe. It is always desirable to have this contact point as near as possible to the fulcrum in order that the frictional contact will not cause rotation of the shoe. The moment of the frictional contact about the fulcrum tends to produce increased wear at the edge of the shoe, whereas it is desirable to have the wear uniformly distributed over the surface of the shoe.

The effect of this camber is also to give additional distance of the end horn below the plane of the contact wire and this might be considered equivalent of a longer end horn and in this respect is an advantage.

As regards the use of side guards I find that if a contact wire should be so far from the center of the track that this displacement, together with the side sway of the pantograph, would cause the entire shoe to be clear of the contact wire, there will not be anything to prevent the pantograph from ascending to its maximum height. There would then be a decided lateral pressure as the car or locomotive proceeds due to the displacement being only local. This pressure of the contact wire against the side guards would be sufficient to tear loose the catenary hangers or wreck the entire pantograph. This, however, would be a very unusual occurrence and could result only due to unusual conditions.

The purpose of the side guards is mainly to prevent hooking of the contact wire when approaching a point where the main line and siding contact wires meet or cross. As the pantograph approaches this point there is a certain location where the distance between the wires is just sufficient to permit one wire to be caught under the end horn. Due to this the contact wire must have sufficient slack so that it will raise above the normal height, due to the pantograph pressure, far enough so that the end horn will pass over the adjacent wire. Either the end horn is broken, the pantograph is wrecked, or the overhead construction is damaged. With a tension in the system well maintained, there is probably not much use for side guards. On a main line operating at high speeds it is essential that the tension be maintained. It is also essential in a line of this character to have the movable pantograph parts as light as possible. Side guards necessarily add to the weight of the movable parts. There are, however, installations where maximum speeds are rather low and where the pantograph operating range is limited so that frequent tension adjustments are not essential provided there is no danger of catching the end horns. In this case side guards become very useful as no matter how slack a siding wire may be the side guards possibly prevent hooking over of the end horns.

The same result is obtained with pantographs of the so-called hornless type. In these the upper frame is so shaped that the side member becomes a guard and only a very short horn is required. The construction is not so good as the frame becomes more complicated. The guard is apt to be damaged and where these are attached to the standard upper frame, damaged guards may be easily removed but when the guard becomes a part of the upper frame the entire pantograph may be put out of commission due to a guard failure.

Investigation of Rail Impedances

Discussion of a paper by Howard M. Trueblood and George Wascheck published in the December 1933 issue, p. 898–907, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 450–1.

H. M. Trueblood: Mr. Harry Brown suggests that the impedances of circuits involving 2 rails would be of interest. Although there was not space in the paper to take up such matters, the impedances of circuits made up of rails or tracks (including parallel paths in the earth), trolleys, feeders, etc., can be computed by using the data in the paper to obtain ground-return self-impedances, along with the ground-return mutual impedances of the various conductors involved, following the methods given, for example, in the paper by Carson (reference 2 in the paper). Such methods have, in fact, been used for a number of years in work on inductive coördination with electrified railways. The impedance of a track circuit to signal current can be calculated similarly, although here it would probably not be necessary to take account of the earth.

These comments by Mr. Brown and also the closing remark in Messrs. Maurer and Sunde's discussion raise the question whether the impedance characteristics of a rail are appreciably modified by the proximity of another current-carrying rail at gauge distance, or perhaps at usual third-rail separations. In the tests, in connecting the rail to the secondaries of the power supply transformers, what was done, in effect, was to impress upon each longitudinal filament of the rail sample an a-c voltage which was the same, at least between potential measuring taps, for all such filaments. If by means of current in a parallel conductor an additional voltage, V', likewise the same for all filaments, were also impressed, and the effects would be (1) to change the components of current density at each point of the rail cross-section—and hence the components of total rail current—by the same percentage of their previously existing values, and (2) to change the voltage drop at every point of the rail periphery and in each exploring wire by this same percentage. The effect of adding the voltage V' upon the surface impedances would therefore be nil, and the shape of the magnetic field in the vicinity of the rail would not be changed. Hence, effects of currents in parallel conductors upon the internal impedance and upon the position and size of the circle for calculating external reactance can only arise from a lack of uniformity over the rail cross-section of the longitudinal electric field due to the parallel current. With one ampere in a parallel conductor at standard gauge distance, the maximum variation in this field over the cross-section of a 130-lb rail is from 2 to 4 per cent of the internal reactance (25 cycles). In the case of a third rail at a separation of two ft this percentage is from 5 to 9. It seems obvious from these figures that the effects of the proximity of current in adjacent conductors at ordinary separations can be neglected in engineering work. As a matter of fact, it was found in the tests that results for the surface impedances were the same when the upper side of the current supply rectangle (Fig. 1 of the paper) was 9 ft from the rail and when it was 5 ft from the rail. Also, in the measurements by Benda referred to in the paper, the corresponding conductor was only a little over 3 ft from the rail, while his results for the shape of the field, etc., were much the same as ours.

Concerning the effect of earth-currents upon the test results, measurements were made on the same rail sample, first in the ordinary position and then inverted (flange upward). The results for the surface impedances were the same for these 2 positions within the precision of the measurements, showing the effect in question to be negligible. It was also found that placing an isolated rail at gauge distance had no effect on surface impedances.

Stabilized Feed-Back Amplifiers

Discussion of a paper by H. S. Black published in the January 1934 issue, p. 114–20, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 461–2.

F. A. Cowan: H. S. Black's paper describes certain principles by which it has been possible to achieve amplification of extraordinary constancy and freedom from nonlinearity. One application of a similar principle to reduce rather than amplify the magnitude of electric currents may therefore be of some interest.

The long lines department of the American Telephone and Telegraph Company employs a large number of telephone repeaters in connection with the operation of long distance telephone and telegraph service. The vacuum tubes in these repeaters are almost universally supplied with filament power from 24-volt storage batteries. It is the usual practice to operate these batteries on a so-called full float basis. When this method of operation is used it is customary to insert electrical filters between the batteries and the filament circuits of the telephone repeaters so that ripples in the battery voltages, caused by the charging machines, may not cause noise to be introduced into the telephone circuits. These filters have been found to be very effective but at certain offices employing batteries with a very large capacity, it has been found that the currents flowing between the charging machine and the batteries set up electromagnetic fields, the fluctuating components of which act upon the transformers in the telephone repeaters and introduce noise. This noise is, of course, greater for those repeaters so located as to be nearest the closed loop formed by the charging and battery bus bars. The relocation of the filter so that it will be between the charging generator and the battery would not be practicable because the battery is used for other purposes which in themselves would introduce some noise and a filter in the present location would still be required. Various methods have been considered for reducing the noise from this source, some of which are:

1. Place electromagnetic shielding around the transformers and repeaters.
2. So rearrange the battery bus bars as to reduce the effective size of the closed loop in which the noise currents circulate.
3. Introduce a filter in the charging circuit leads.
4. Provide some low impedance shunt for the noise currents near the charging generators.

As may be noted in Mr. Black's paper the feedback circuits of the type described have the effect of reducing noise by the factor $\frac{1}{1-\mu\beta}$. If both the input and output of a suitable amplifier are connected across a circuit the voltages which existed in the circuit prior to connecting the amplifier will be reduced by about the amount of the foregoing factor. This has been tried out in the field by connecting a single special amplifier across the charging generator of a power plant. It was found possible in this case to make reductions in the noise produced by the ripples in the battery charging current corresponding to a power ratio of about 100 to 1. The limiting factor appears to be the power carrying capacity of the amplifier and for power plants of considerable size relatively powerful tubes are required in the output stage or several tubes in parallel may be needed. However, under certain conditions, the cost of this arrangement may prove to be less than the other plans considered.

Although this method of reducing noise was suggested by consideration of feedback such as was discussed by Mr. Black, a review of certain technical literature has shown that Mr. Crisson in his paper "Negative Impedances and the Twin 21-Type Repeater" (see *The Bell System Tech. Jl.*, July, 1931) considered, the action of circuits of the type employed in the foregoing application. A study of Mr. Crisson's paper would be helpful to one desiring a more complete understanding of the principles involved.

Cast Iron and Its Production

Discussion of a paper by M. V. Healey published in the January 1934 issue, p. 120–3, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–3; 455.

W. E. Moore: Mr. Healey has well set forth the outstanding advantages of electric iron in comparison with cupola iron and has been quite fair to the argument throughout.

The concise explanations which he makes as to the physical reasons for more homogeneous and generally better quality of electric over cupola iron have been given with an unusual degree of clearness.

He is quite correct that for ordinary mechanical purposes electric furnace iron is far superior in physical properties and in uniformity, and that no alloying is ordinarily required.

Electric iron by superheating in a direct polyphase arc furnace develops superior physical properties merely by the complete solution of the carbon or graphite nuclei in the iron held molten at high temperature in a way that is utterly impossible in the cupola, and furthermore is refined by proper slagging action.

While the so-called air furnace or open hearth furnace is capable of developing a higher temperature in the iron than the cupola, the temperature is still not sufficiently high to dissolve entirely all of the carbon-graphite particles necessary to produce the improvement so marked in physical properties characteristic of electric iron. Nevertheless the so-called air furnace iron has long been known as a superior quality iron and in former times was known as "gun iron" because cupola iron was too unreliable and too irregular for casting cannon.

The ability of the electric furnace to make cast iron of low carbon content is also of marked advantage as compared to the cupola, particularly when molding thick castings, such as rolls and heavy machinery, where there is with cupola iron a marked difference between the grain structure of the iron at the surface and on the interior of the casting.

Electric furnace iron containing a high percentage of steel scrap for such wearing parts as tube mill liners and grinding balls used in the ore milling industry are now produced not only cheaper than by the cupola process, but with a life 200 to 300 per cent greater.

The electric furnace used in Mr. Healey's experiments shows a production in a 3 ton furnace of 5 tons in 3 hr or $1^2/_3$ tons per hour, which indicates that it is of an older slow-type furnace. With the modern arc furnace of the same rating 3 tons or more of cast iron per hour can readily be produced when "cold melting" and it may also be operated to advantage on a continuous melting cycle where so desired.

Since electric furnaces can be run all day and produce a steady flow of hot metal ready for tapping, it is thus quite practicable to operate the molding floor continuously, which requires far less flask equipment and floor area than that required with the cupola process where the heat is concentrated into 2 or 3 hours of melting in the afternoon.

The greater strength and toughness of electric furnace iron should be a sufficient advantage to cause users of machinery to specify, where obtainable, that the equipment they purchase will be made from electric iron.

Electric furnaces may be used for duplexing to splendid advantage, the metal being melted in a cupola, brought in a ladle (or spouted) to the electric furnace, and the electric furnace operated on a "continuous cycle" delivering small ladles of superheated metal at frequent intervals, and at corresponding intervals receiving molten but not superheated metal from the cupola. The metal thus refined in the electric furnace has the same superior properties of iron that has been cold melted in the electric furnace and the furnace, of course, has greatly increased capacity. In a case where a half ton per hour modern type direct arc furnace is operated in this manner, a molten bath of $1^1/_2$ tons is maintained in the furnace, a flow of over 3 tons per hour of metal is refined in the electric furnace. This metal is used for continuous pouring in machine conveyor molds with highly economical results. In this case the power consumption is averaging less than 50 kwhr per ton; the electrode consumption 2 lb of graphite per ton, and the refractory cost is $0.16 per ton.

Another larger installation of electric malleable iron duplexing furnaces averages 20 tons per furnace per hour; 2.5 lb of graphite electrodes per ton, and under 50 kwhr per ton power consumption, and under $0.05 per ton refractory maintenance.

In one plant some 4,000 electric-iron automobile brake drums are cast per day, along with 1,000 camshafts, with most satisfactory results.

In another plant 2,000 automobile crankshafts are now cast per day of electric-iron, giving a highly superior product, having an elastic modulus of more than 30,000,000 lb.

The electric furnace in the cast iron foundry has produced a revolutionary prod-

uct, a new engineering material, opening up new economies and with possibilities previously unknown. Electric iron will have a widespread and growing use and add new life to the iron foundry upon which the steel foundry and welding shops have made severe inroads.

Rocking Indirect Arc Electric Furnaces

Discussion of a paper by E. L. Crosby published in the January 1934 issue, p. 132–8, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–3; 454–5.

W. E. Moore: The development of the Electro-Metallurgical furnaces has been quite remarkable since the beginning of the Twentieth Century, although hampered initially by high costs and lack of suitable power supply. With the ample Central Station Power Supply and reasonable rates now obtainable the further advance of the Electro-Metallurgical furnace will be rapid indeed, particularly in connection with the rapid development of stainless steels, alloy steels, and electric cast iron.

The indirect arc or Rocking type electric furnace was one of the early Electro-Metallurgical developments, as was evidenced by the Stassano furnace and others. The use of an indirect arc struck between horizontal or approximately horizontal electrodes is also old, but those furnaces have generally had more or less delayed development due to the greater surface of electrodes exposed to oxidation and to their horizontal position which has caused increased breakage so that the horizontal electrode furnace has always had against it a high electrode cost.

With a horizontal arc the flow of heated gases between electrodes is deflected upward by air currents; in fact, it was due to this effect that Sir Humphry Davy named it the electric arc. When the arc is diverted by heated air currents, the arc stream being no longer coaxial with the electrodes, is subjected to magnetic repulsion or "blowing" which further accentuates the divergence in an upward direction. This upward divergence is unfavorable to refractory roof life.

In distinction the direct arc type of furnace with single vertical electrode and current return through the charge and bottom was the first form of commercial Electro-Metallurgical furnace, as with that design instead of exposing two electrodes, as with the horizontal indirect arc furnace, there was only one electrode exposed to oxidation. A number of these furnaces are still in commercial use, but owing to the demand for larger furnaces and after the power supply became universally three phase, the trend became notably toward larger electric furnaces of the vertical electrode polyphase direct arc type.

The improved screw jointed continuous electrode was a great improvement over the old single piece electrode in which a large portion or "butt" had to be discarded after use. The screw jointed electrode made the trend toward the vertical electrode furnace still more accentuated.

As the furnaces grew larger in size the disadvantages and complications of carrying the current direct through the furnace metal structure either vertically or horizontally became more apparent, as the iron structure of the furnace shell introduced large reactive drop and iron losses with a heavy secondary current flow directly through the surrounding iron work, consisting of shells, heads, etc. With the polyphase electric furnace the currents all being carried in through the nonmagnetic refractory roof with the electrodes closely paralleled and the cables spaced near together, the power factor conditions were much improved.

With the vertical electrode furnace it also became practicable to have a convenient operating door or doors through which the charge might be placed in the furnace, or the slag or heat worked in the desired manner. The wearing areas of banks or refractory surfaces wetted by the slag were also at a minimum, and the refractory lining most remote from the heat of the arcs so that the wear and maintenance on the refractories was at a minimum.

With the vertical electrode furnace the electrodes arc directly to the metal—the heavy current passes through the metal of the bath when superheating, using the slag in part as a resistor medium, the arc craters closely facing and radiating directly toward the bath. This effect is to superheat the metal in the center of the bath causing a thermo-syphon-circulation upward through the center of the bath, then radially outward toward the sidewalls, down along the bottom, and back up the center—a quiet non-turbulent circulation that exposes all parts of the metal to the purifying effects of the slags, to the superheating effects of the arcs, and allows all non-metallic inclusions ample opportunity to coalesce with the slag blanket covering the metal.

With the direct arc furnace it is practicable to run a reducing or an oxidizing atmosphere merely by the door adjustment on the furnace, the arcs may be of any advantageous length, as for instance made longer in the manufacture of low carbon alloys. Through the ample workroom sidedoor it is easy to take samples to check the adjustment of the mixture as to carbon, sulphur, phosphorus, or other alloys in a manner not possible in the small door drum type furnace. If the sulphur be too high that can be reduced by a lime slag and the same applies to the phosphorus content; if the carbon be too high that can be adjusted as by the addition of ore. One does not therefore have to melt carefully weighed and cleaned scrap of known and uniform composition like in crucible melting, and depend upon a watthour meter to tell when the temperature is right as with the closed drum type furnace.

The vertical electrode furnace is ideal for refractory maintenance, since the sidewalls being vertical do not tend to cave in and the bottom may be of either shaped refractories or cheaply rammed in granular material, and may be readily fettled or repaired by shovelling in additional granulated material between heats when desired. The roof being of arched spherical form gives freedom for expansion and supports itself in an ideal manner. As might be expected, the refractory maintenance on the vertical electrode direct arc furnace is very low. In the rapid melting type acid furnace refractory maintenance rarely goes above $0.25 per ton on batch cold melt practice and as low as $0.15 or better per ton, for material and labor. Likewise the electrodes being held in the most favorable position show minimum breakages and, being of short length, show minimum consumption by oxidation, so that it is rarely the case that the electrode consumption on the vertical electrode direct arc rapid type furnace exceeds one-half to two-thirds that required by the larger size horizontal electrode single phase indirect arc furnace.

The direct arc electric furnace is particularly well adapted for cast iron melting and it is quite easy to get any degree of superheat to completely dissolve, without difficulty, the graphite nuclei. The graphite having once all been put into solution, which is not possible in the cupola, does not contain focal points, as in cupola iron, around which the segregating graphite may grow and produce flaky-weak structures or cleavage planes in the metal.

The refining and metal manipulation under a slag is one of the most valuable features of electric furnace work for without a slag blanket there is no appreciable refining.

With an all-scrap charge readily machinable castings may be produced without difficulty in a direct arc electrical furnace using an all-scrap charge—a thing not practicable with cupola melting. In like manner the electric furnace is just as adaptable for white or chilled iron making, such as chilled iron rolls, wearing plates for crushers, ore mill grinding balls for tube mills, or for making white iron castings to be malleablized which must be practically free from graphite segregation in order to make proper strength malleables.

With the arc electric furnace, since the graphite is completely dissolved in the superheated metal and there being no focal points or nuclei around which the graphite may segregate when freezing, a metal higher in silicon may be cast without graphite segregation, which means a metal more readily and more rapidly annealed. In this manner small malleables have been made in the direct arc electric furnace and annealed within a period of four hours.

High strength gray iron is a growing product, made in the arc furnace, and with proper refining even poor grade scrap may be put into the highest grades of high strength electric iron, either alloyed or plain low carbon mixtures.

The rapid type direct arc furnaces are today used in large numbers for high quality gray iron. While electric furnace gray iron has been made commercially for more than 15 years, the demand for it has largely developed within the last 8 years.

There is today in use in this country approximately 125,000 kw capacity of electric melting furnaces on various irons. In this field approximately 80% of the capacity is of the polyphase direct arc melting and refining type. The total electric melting furnace load in the U.S. today amounts to approximately 600,000 kw capacity. This load may be expected to total over 1,000,000 kw within the next ten years.

High Frequency Induction Furnaces

Discussion of a paper by C. A. Adams, J. C. Hodge, and M. H. MacKusick, published in the January 1934 issue, p. 194–205, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–3; 455–6.

H. Poritsky: This paper gives a good review of furnace design. We should like to present in greater detail the theory of inductive heating. First we shall review the circuit equations of a transformer. These apply essentially to the iron core low frequency furnace.

The circuit equations of the transformer, in complex vector notation, are:

$$\left.\begin{aligned} Z_1 I_1 + Z_{12} I_2 &= E \\ Z_{12} I_1 + Z_2 I_2 &= 0 \end{aligned}\right\} \tag{1}$$

where

$$\left.\begin{aligned} Z_1 &= R_1 + j\,(L_1\omega) \\ Z_{12} &= jM\omega \\ Z_2 &= R_2 + jL_2\omega \end{aligned}\right\} \tag{2}$$

Eliminating I_2 we obtain

$$\left(Z_1 - \frac{(Z_{12})^2}{Z_2}\right) I_1 = E$$

Thus the effect of the secondary is the same as if an impedance

$$\left.\begin{aligned} Z' = R' + jX' &= -\frac{(Z_{12})^2}{Z_2} \\ &= \frac{(M\omega)^2}{R_2 + jL_2\omega} = \frac{M^2\omega^2(R_2 - jL_2\omega)}{R_2^2 + L_2^2\omega^2} \end{aligned}\right\} \tag{3}$$

were introduced in series with the primary.

The power delivered to the secondary is

$$P_2 = \frac{1}{2}\left|I_1\right|^2 R' = \frac{1}{2}\left|I_1\right|^2 R_2 \frac{M^2\omega^2}{R_2^2 + L_2^2\omega^2}, \tag{4}$$

where $|I_1|$ is the peak value of the current. The power delivered to the primary is

$$P_1 = \frac{1}{2}\left|I_1\right|^2 R_1 \tag{5}$$

Hence the efficiency

$$\eta = \frac{P_2}{P_1 + P_2} \tag{6}$$

can be found. Note also that if in (4) we replace I_1 by E/Z we obtain

$$P_2 = \frac{1}{2}\frac{|E|^2}{|Z|^2} R' = \frac{|E|^2}{2}\frac{|Z_2|^2 R'}{|Z_1 Z_2 - Z_{12}|^2}$$

$$= \frac{|E|^2}{2} \frac{R_2 M^2\omega^2}{[R_1R_2 + (M^2 - L_1L_2)\omega^2]^2 + \omega^2 (R_1L_2 + R_2L_1)^2} \tag{7}$$

Suppose now that R_1, R_2, L_1, L_2, M are constants (independent of ω) then it follows from the above that the efficiency η increases with ω, varying as ω^2 for low ω and approaching

$$\frac{1}{1 + \dfrac{R_1}{R_2}\left(\dfrac{L_2}{M}\right)^2} \tag{8}$$

for large ω.

While for the same furnace $P_2/|I_1|^2$ continually increases with ω approaching the value $M^2\omega^2/2R_2$ for large ω, the ratio $P_2/|E|^2$ behaves differently. Indeed, from eq 7 we see that $P_2/|E|^2$ increases as ω^2 for small ω and decreases as $1/\omega^2$ for large ω; it must therefore exhibit a maximum. This is taken on at

$$\omega^2 = \frac{R_1R_2}{L_1L_2 - M^2} \tag{9}$$

Roughly speaking, the above equations show why removal of the iron core requires an increase in frequency. Indeed, from eqs 4 and 5 follows

$$\frac{P_2}{P_1} = \frac{R_2}{R_1}\frac{M^2\omega^2}{R_2^2 + L_2^2\omega^2} \tag{10}$$

Now if M, L_2 have both been reduced in a certain ratio through the removal of the core, it is necessary to increase ω in the same ratio in order to obtain the same P_2/P_1 and hence the same efficiency.

If one attempts to apply the above equations to coreless furnaces and high frequencies, caution must be observed to replace $R_1, R_2, \ldots$ by proper equivalent values that can be calculated only when the current distribution is known. This, as will be shown later, can be done both for low and high frequencies. Before considering this let us see what results may be obtained by means of dimensional analysis.

Dimensional analysis can be used to advantage in investigating the effect of size, frequency, resistivity. According to its principles any relation between physical quantities must reduce to a relation between dimensionless combinations of these quantities. Thus if it is granted that the efficiency η depends on the size as characterized by some length l, on the resistivity ρ, the permeability μ, and the frequency f, then it follows that the relation sought

$$\eta = f\,(l, \rho, \mu, \omega)$$

must reduce to an equation

$$\eta = f\left(\frac{\mu\omega l^2}{\zeta}\right) \tag{11}$$

since, with 4 fundamental units, say of mass, length, time, and permeability, $\mu f l^2/\rho$ is essentially the only dimensionless combination of the 4 quantities l, ρ, μ, f. This shows, for instance, that if in a test with a model, a certain efficiency has been reached at a proper frequency, that a larger size will allow the frequency to be decreased as the square of the size increases and the same efficiency will be obtained. (Strictly speaking, this conclusion follows from dimensional analysis only if the primary coil, too, be geometrically magnified.) Again, if the *tonnage* of a furnace be increased say r-fold by proceeding to a larger furnace of similar design, the dimensions will be magnified as $r^{1/3}$, while a decrease of frequency in the ratio $r^{2/3}$ will lead to the same efficiency.

As already pointed out in connection with eq 10, a change in μ can be compensated for by a reciprocal change in ω. However, this change in μ means now that the permeabilities of *all* points (air included) be changed in the same ratio. Hence the result is only of qualitative value.

For P_2 we obtain similarly by dimensional analysis

$$\frac{P_2\rho}{l|E|^2} = f\left(\frac{\mu\omega l^2}{\rho}\right) \tag{12}$$

From this we may conclude that the value of ω that renders $P_2/|E|^2$ a maximum varies inversely as the square of the furnace size.

A more detailed analysis of the coreless furnace shows that:

1. η, $P_2/|I_1|^2$, $P_2/|E|^2$ all vary as ω^2 for small ω.
2. $P_2/|I_1|^2$ continually increases with ω, varying as $\sqrt{\omega}$ for large ω.
3. The efficiency η increases with ω and approaches a limiting value (<1).
4. $P_2/|E|^2$ takes on a maximum value for a proper ω, and eventually decreases as $\omega^{3/2}$

Consider first frequencies so low that the induced currents are small compared to the primary current, so that the magnetic field is essentially the same at each instant as the d-c field corresponding to the instantaneous value of primary current. The magnitude of the induced electromotive force as well as of the induced currents will vary as the *rate of change* of the field, hence as ω. The power P_2 will thus vary as

$$P_2 = (\text{const.})\ |I_1|^2\omega^2\rho \tag{13}$$

The constant can be determined from a flux plot Similar formulas are easily proved for η and $P_2/|E|^2$. The induced currents are 90 deg out of phase with I_1.

Suppose next that the frequencies are high so that the field due to the induced currents becomes of the same order of magnitude as the field of the primary current. For these high frequencies the effect of the field of the induced currents in itself inducing currents is so large, that the induced current, so to speak, trip over themselves. This constitutes the phenomenon of "skin effect" according to which both the field and the currents penetrate but a small distance into the conducting solids.

The simplest case for investigating this phenomenon is offered by a uniform tangential field that is applied at the boundary of a semi-infinite solid of resistivity ρ and permeability μ.

In this case the solution of Maxwell's equation shows that the electric and magnetic vectors are at right angles to each other, that their amplitudes decrease exponentially with the depth of penetration, decreasing to $1/e$ of their boundary values in the depth

$$T = \frac{1}{2\pi}\sqrt{\frac{\zeta 10^{-9}}{\mu f}} \tag{14}$$

where practical cgs units are used.

The quantity T can be used as a general index of how pronounced the skin effect is for any shape solid: if the dimensions involved are larger than T the effect will be pronounced, if less they will not. Indeed, in other cases in which the complete field distribution have been obtained theoretically, for instance, in the case of an infinitely long charge in a uniform solenoid,

it is found that at high frequencies the distribution of flux and eddy currents conforms to the above type. On physical grounds this may be predicted from the fact that if the depth of penetration T is considerably less than the radii of curvature of the boundary, the latter may be effectively considered plane.

In applying the above to a coreless furnace of dimensions greatly exceeding T, it is commonly assumed that magnetomotive force of the primary coil is consumed on its inside. This determines the applied field in terms of ni, the primary, ampere turns per unit height. The induced electric field at the boundary comes out to be

$$H = Z_0 (ni)$$

where

$$Z_0 = (1 + j)\, 2\pi\sqrt{\rho\mu f\, 10^{-9}} \tag{15}$$

Neglecting and effects due to the finite size of the coil and charge, the effect of the secondary may now be shown to be equivalent to an impedance

$$Z_2 = N^2 A Z_0, \tag{16}$$

where A is the area of the charge covered by the primary, N the total number of turns.

From eq 16 it will be seen that Z_2 varies as $\sqrt{f}$ or $\sqrt{\omega}$. Thus, for a given I_1 the power P_2 will increase continually as $\sqrt{f}$. It is also concluded that R_2 and X_2 $(= L_2\omega)$ tend to become numerically equal for high ω.

At first glance it would appear that since P_2 rises indefinitely with f, that the efficiency could be made close to unity by choosing a high enough frequency. This, however, is not the case, as soon the skin effect appears in the primary winding, too. For a rectangular closely wound coil, the limit P_2/P_1 approaches $\sqrt{\rho_2/\rho_1}$, where ρ_2, ρ_1 refer to the secondary and primary, respectively (assuming permeabilities = 1) and η approaches

$$\frac{\sqrt{\rho_2}}{\sqrt{\rho_1} + \sqrt{\rho_2}} \tag{17}$$

Actually this limiting efficiency is further decreased due to the larger radius of the primary and to the space between the windings. Such a corrected value was obtained by Burch and Davis by means of a complex analysis.

While Z_2 as given by eq 16 takes care of the voltage due to the secondary, it does not take account of the voltage due to the flux in the gap between the primary and secondary. Now Z_2 varies as $\sqrt{\omega}$ but the latter voltage varies as ω and thus the reluctance of the air space will be the limiting factor for the current I_1 at high frequencies, and will cause the power factor angle of the furnace to increase from the 45 deg angle displayed by the skin effect formulas toward 90 deg at high frequencies. Hence, for large ω

I_1 varies as E/ω

P_2 varies as $(E^2/\omega^2) \cdot \sqrt{\omega} = \dfrac{E^2}{\omega^{3/2}}$. Thus for the coreless furnace, too, $P_2/|E^2|$ first increases as ω^2 then decreases (as $\omega^{-3/2}$ and will possess a maximum.

The above elementary treatment can be improved and some of the neglected factors included. It is also possible to cover the commercially important intermediate frequencies at which the fields due to the induced currents cannot be neglected, and yet the skin effect is not so pronounced as to concentrate the eddy currents at the surface. This has been accomplished by a combination of powerful analytical and graphical methods relying on successive approximations.

The 3-Phase Electric Arc Furnace

Discussion of a paper by Samuel Arnold, 3rd, published in the December 1933 issue, p. 839–43, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–4.

W. E. Moore: The writer has specialized for some years on the development of the fast making polyphase direct arc furnace. This principle of operation has been developed to the extent that arc furnaces, instead of making 3 to 4 heats per 24-hr day, as formerly, now frequently run 6 to 18 heats per day of 24 hr, with correspondingly increased output, greatly improved electrical efficiency, reduced consumption of electrodes and refractories and with decreased labor costs.

With this type of direct arc furnace the efficiency is high because the time of heat loss during the heat is short and because the heat is applied directly to and in the metal. The refractories also are favored in that they are normally maintained under a soaking heat for but a comparatively short time, namely, during the superheating portion of the furnace cycle and thus are cooled when a repetition of the melting cycle again permits them to release heat to the next metal charge.

This type furnace has been so designed for electrical stability as to permit the use of arcs of much higher voltage than was the prior custom so that electrode diameter and cross section of load carrying parts has been correspondingly reduced. With these longer arcs the possible stability of the furnace is also improved by reason of any irregularities in the scrap charge forming a smaller portion of the total arc length.

With rapid work the furnace efficiency has been so improved that on acid steel and iron melting and refining, when operating under favorable conditions, the power consumption can be assumed to be 500 kwh per ton and sometimes goes as low as 450 kwh per ton melted and superheated. However, on smaller furnaces and furnaces on slow discontinuous operation the unit power consumption is not so good. By the same token the electrode consumption has been reduced to as low as 8 lb per ton with carbon electrodes and with graphite electrodes as low as 4 lb per ton; in fact, one user reports 2.82 lb of graphite electrodes per ton charged yearly average; although this electrode consumption would necessarily not be so good on furnaces of the smaller sizes or when operating under slow part-time conditions.

With the direct arc furnace it is quite practicable to make low carbon products without carbon pick up, quite in contrast to the older style slow arc furnaces in which it was considered practically impossible to make low carbon heats such as ingot iron, permalloy, or remelting stainless iron without undesirable carbon "pick-up."

To the 3 classifications of furnaces mentioned in the paper should be added 2 others; namely, class (4) continuous melting, and class (5) continuous refining, in which the furnace is kept continuously supplied with a bath throughout the operating period—whether that be by the day or by the week—the metal being tapped off at frequent intervals in comparatively small ladles in quantities ranging usually from 10 to 25 per cent of the holding capacity—and corresponding charges added at frequent intervals. With this type of furnace insulated refractories are especially desirable. In fact, furnaces fitted with insulated refractory linings have been in use for the past half dozen years or more showing reduced heat losses—both for batch melting and continuous melting. An insulated refractory lining is, however, more costly in installation and maintenance so that operators ordinarily prefer to use a rapid type furnace to obtain high efficiency with the standard-shaped-refractory-linings.

Now that ample central power supply is available it is entirely practicable to construct direct arc polyphase electric furnaces of 25,000 kva capacity and greater.

Large furnaces may be fitted with side doors of sufficient size to permit the ordinary open-hearth-type-horizontal-charging machine to be used for mechanically charging the furnace. While this is an improvement over hand charging, it is still not a rapid means of charging and permits a marked "cool-down" of the furnace between heats, also a large loss of time during which power demand must necessarily continue to be charged and it is rough on the furnace structure and refractories; it does not permit of filling the furnace with a full charge up to the electrodes, as is necessary with bulky scrap to avoid recharging.

This difficulty has now been successfully overcome by the top-charge furnace. The top-charge furnace roof is lifted slightly and swung to one side by means of a hydraulic cylinder, uncovering the entire opening in the furnace crucible, and the charge contained in a cylindrical bucket with orange peel bottom opening is lowered into the furnace and deposited at one time without delay and to the full capacity of the crucible and without injury to the refractories or electrodes. This process frequently requires only a period of 4 min from "tap" to power on again—in contradistinction to the period often ranging from one-half hour to one hour or more for charging the old side door furnace. This correspondingly improves the output of the furnace without increasing the demand charge, and with an economy in the unit power consumption due to shorter time for heat losses during the furnace cycle. It also reduces the time in which the white hot electrodes are exposed to oxidation in the outside atmosphere as well as reducing the lost time of the attendants. Top-charging also allows the use of large scrap. This improvement has in certain cases reduced the melting cost from $1.50 to $2.00 per ton—although the furnace plant is somewhat more expensive

in first cost. More than a dozen top-charge furnaces have been installed.

The electrodes and refractories of the roof, not being tilted are not strained, weakened, nor broken while charging and the marked advantages of quicker time are thus gained without resulting in disadvantageous conditions.

With the modern direct arc furnace it is standard to use a transformer having 4 or more voltage connections, and the usual voltages for such operating requirements as are standard for any given operation are made available at the switchboard. Provision is also made for stabilizing the power to the furnace at whatever arc voltage may be in use.

With the modern direct arc electric furnace the cost of the furnace installation for a given daily production is now less than that obtainable for modern open hearth furnace installations, and is in active competition with the open hearth furnace. Approximately 80 per cent of the tonnage of electric iron is at present furnaced in direct arc furnaces.

The connected capacity of direct arc furnaces in the United States now totals some 600,000 kw, and with a return of activity in steel and other metallurgical enterprises it is estimated that within the next ten years an increase of 400,000 kw in electric furnace load may be confidently expected.

The following table shows an estimated cost per net ton for a modern rapid-melting type direct arc top-charge polyphase electric furnace when in steady, continuous operation, under favorable conditions:

500 kwhr @ 0.6¢	$ 3.00
10 tons steel melting scrap @ $12 per ton	6.00
10 tons steel turnings @ $8 per ton	4.00
Plus melting loss—3 per cent	.30
8 lb carbon electrodes @ 7¢	.56
Ferro-alloys and slag additions	1.20
Refractories maintenance	.20
Furnace attendants	.24
Cost per ton of steel at spout (not including ladle, mold nor overhead costs)	$15.50

Samuel Arnold, 3rd: The discussion by W. E. Moore is very interesting and brings out a number of points worth considering. I agree entirely with Mr. Moore that there is quite a difference between modern furnaces and furnaces of the older type. Modern furnaces are usually equipped with high power transformers, higher voltages and multiple voltage control so that the operator may choose at will the voltage most adaptable to the furnace conditions. The rate of melt is, of course, directly proportional to the rate of power input and as I mentioned in my paper, efficiencies have been increased materially by decreasing the time of radiation. Today all direct arc furnaces in common use are of the Heroult type and there is very little difference in the general dimensions of the shell. The most important differentiation being in the method of tilting and the method of operating the electrode arms. The effective voltages used for a given power input are also practically the same. It is my opinion, however, that the melting voltage to be used is largely dependent upon the amount of power to be introduced. This is especially true in the larger units and I might add that on a 50 ton Heroult furnace, melt down voltages are available as high as 290 volts across phases which I believe are the highest voltages that have ever been used on production work.

I wish to point out, however, that in my paper I gave due recognition to the use of higher power inputs but mentioned that some thought should be given to increasing the efficiency of the furnace along other lines. This for the reason that high demand charges often penalize the furnace operator and with a comparatively low load factor the high cost of power frequently more than offsets the gain obtained by decreasing the kilowatt hours per ton.

With regard to insulation as a means of increasing furnace efficiency, I know that this has been tried from time to time but from all the data I have been able to gather, has not been tried with any real degree of engineering application. At the time of giving the paper, some experiments were being conducted with a small arc furnace, utilizing insulating brick in the side walls and to date these experiments have indicated that further efforts along this line would be warranted. The first lining life of this small unit of approximately one ton nominal capacity was 207 heats with acid operation and the power costs were reduced about 50 kwhr per ton with a demand charge of approximately 80 per cent of that necessary without the insulation, based on the same tonnage being produced. The question of the added cost of this insulating material as opposed to the savings obtained and just how far the insulation can be carried are, of course, open at the present, but there is every reason to believe that advantages accrue from insulating electric furnaces, and I again wish to emphasize the desirability of further experiments.

Mr. Moore mentions that continuous melting and refining furnaces should be added to the classification. This is simply a question of nomenclature and I prefer to use the term semi-continuous melting and refining for the reason that the metal is tapped and charged at intervals.

Mr. Moore further mentions that it is entirely practical to construct direct arc polyphase furnaces of 25,000-kva capacity and greater. He does not say but I believe he means that in these larger capacities, multiple electrodes are necessary. In my paper I mentioned a 6-electrode 20,000-kva furnace and from data so far obtained on the operation of this unit, it is questionable if higher kilowatt capacities can be used per electrode and that any increase in capacity would mean additional electrodes.

As to the open or removable roof type of charging, this method has been successfully used on furnaces from 3 to 10 tons in capacity, but I question very much the efficiencies claimed by Mr. Moore for this type of furnace. Heroult furnaces have been built and are in use utilizing this method of charging which, of course, shows economies over hand charging primarily on account of the time saved, but when it is considered that a furnace is opened up and that there are two large radiating bodies at a temperature of 3,000 deg F or above, you can easily visualize the tremendous loss of energy even in a very short period of time. This was brought out in the moving pictures shown where it was noted how rapidly the brick lose their temperature and become blackened. With furnaces from 1 to 3 tons, I believe the chute method of mechanical charging is the best. With furnaces from 3 to 10 tons in capacity it is an open question as to the efficiency of the removable roof type, and on furnaces from 15 tons capacity up, the open hearth charging machine is unquestionably the best method of charging that so far has been developed.

Mr. Moore's data on melting costs are very interesting. I wish that I could agree that average costs would be somewhat in line with what he has given. In the first place, if steel turnings were used by all electric furnace users as indicated by Mr. Moore, the steel turning market would soon be dried up. In the second place, the labor costs he gives are very much lower than the average. Assuming 48 cents an hour for furnace labor, which is exceedingly low, this would mean that two tons of metal will be produced per man hour. In addition to this, there are a number of other items of costs such as crane charges, scrap handling, water, miscellaneous power, furnace maintenance and other items which he has not included and which should properly be charged to metal production costs. There may be one or two isolated conditions with methods of accounting that would indicate metal costs in line with that which Mr. Moore has given, and if production costs in general could be obtained as low as indicated, open hearths would soon disappear.

I wish also briefly to comment on the discussion of Mr. Frank W. Brooks and Mr. C. C. Levy. I believe that Mr. Brooks is sincere in his statements regarding insulation, but I am not at all convinced that the field should not be explored more definitely. As to ratings of furnaces, standardization is, of course, a fine thing, but today furnace users know something about furnaces and usually it is very difficult to give them something in the line of standard equipment. Nearly always and I believe rightly they wish to incorporate some of their own ideas. As to Mr. Levy's question, I believe I answered this in my paper where I stated that the diameter of the shell, the nominal holding capacity, and the tons per hour for production for a specified product should be given.

Steady State Stability of Composite Systems

Discussion of a paper by S. B. Crary published in the November 1933 issue, p. 787–92, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Another discussion of this paper was published in the March 1934 issue, p. 477.

S. B. Crary: H. L. Hazen brings up the interesting question of how to determine the distribution of loads among the generators of a system when making a stability study. All of the four assumptions discussed by Hazen, may be used in any one stability study. Assumption 1, that the relative rotor position of a group of machines

remains unchanged with respect to each other, is in effect equivalent to considering that group as one equivalent synchronous machine. This is a necessary and practical assumption in many cases. Hazen suggests, by assumption 2, that the inherent speed regulation of the prime mover may be used to determine the load division. This is undoubtedly a worth while consideration in some cases, although in general, the inherent regulation of a prime mover with constant gate or throttle opening is large compared with the regulation of the machines which are governor controlled. Therefore, if the period immediately after the governors of the governor controlled machines have acted is under consideration, the machines with constant gate or throttle openings can be considered as fixed power machines. This assumes that a reasonable ratio exists between the relative capacities of machines under governor control with those that are not.

However, it may be advisable in some cases to make assumption 2, as Hazen suggests. For example, it may be found that using the inherent speed regulation of the prime movers results in lower limits than if governor regulation had been used. The limit of safe operation should accordingly be determined by this more pessimistic result. Each study usually presents problems which makes necessary an examination and evaluation of the assumptions to be used for each case.

Attenuation and Distortion of Waves

Discussion of a paper by L. V. Bewley published in the December 1933 issue, p. 876–84, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 471–3.

Otto Ackermann: Nobody realizes the importance and the significance of L. V. Bewley's paper better than those who, in their regular work, have studied lightning surges and experimented with traveling waves. They often were confronted with and puzzled by wave phenomena which could not satisfactorily be explained on the basis of the conventional theory. The first ones, I believe, were C. L. Fortescue and his staff who obtained klydonograph records with positive and negative characteristics in the same figure from conductors which obviously had carried only induced surges. In his paper presented at the Worlds Power Conference at Paris in 1932, Mr. Fortescue attributes this phenomenon to a peculiar coupling effect involving waves of different speeds whereas formerly it had been erroneously interpreted as indicating an oscillatory lightning discharge.

In Switzerland, K. Berger recorded lightning surges by means of 2 cathode ray oscillographs on parallel phases as early as 1930 and was surprised by finding induced waves starting with a potential opposite to that of the main surge. In the S.E.V. Bulletin, 1931 Nr. 17 one finds his attempt to explain this phenomenon. In 1931, the writer visited Mr. Berger and the discussion brought forth marked coincidence between Mr. Berger's observations and measurements made by the Westinghouse company in coöperation with the Public Service Company of New Jersey. In Fig. 1 is the copy of a lightning surge recorded by Mr. Berger 66 miles from the point of origin (published in the S.E.V. Bulletin, 1932 Nr. 12, p. 295). In Fig. 2 is shown the record of an artificial wave and the induced voltage 5 miles from the origin taken on a line of the Public Service Company of New Jersey. It is only one sample of a great number of similar records showing opposite polarity on the induced surge. Encouraged by the apparent similarity in the behavior of natural and artificial surges Mr. Berger advanced our explanation of the phenomenon in his abovementioned paper in 1932. It may be said now that all these attempts to explain this perplexing phenomenon were lacking considerably in one way or another and Mr. Bewley must be credited with having advanced the complete understanding of a question which has occupied many a student of traveling waves in the last few years.

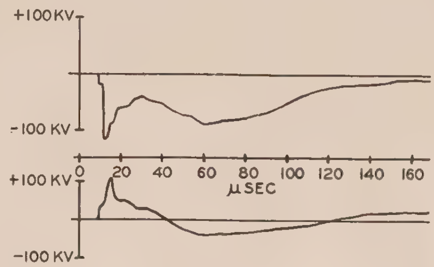


Fig. 1. Lightning disturbance on 2 phase wires, recorded 66 miles from the origin

Retraced from the S.E.V. Bulletin, 1932, p. 295, Fig. 8

However clear the mathematical derivation, the mental picture of this interesting process is somewhat hard to form, since it demands us to imagine a surge creating another one of exactly the same magnitude but of opposite polarity on an isolated parallel conductor. Yet, the final result is exactly the same as if a surge were applied between 2 parallel conductors by means of an impulse generator. In this case, the 2 wires carry equal surges of opposite polarity.

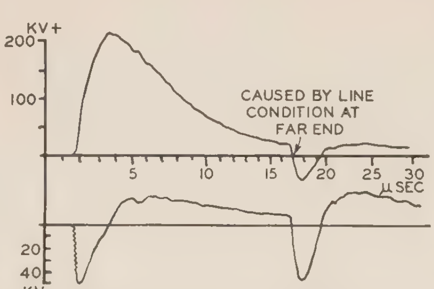


Fig. 2. Artificial surge and induced wave recorded 5 miles from the origin

A surge between line and ground has the inherent tendency to travel at the speed of light. If it is impeded by ground currents or corona, at least such components as can form pure electromagnetic fields of the classical description propagate at full speed. This possibility is given if a second parallel wire in air is present. It carries the opposite charge just as if a surge was applied directly between the 2 conductors. The balance of the charges follows at slower speeds. From this fundamental conception it follows that there always must be a wave component propagating at the speed of light as long as the establishment of a pure undistorted electromagnetic wave between conductors is at all possible. From this standpoint, the faster speed component must always be equal to one. If calculations as in Mr. Bewley's paper, p. 880, columns 4, 5, and 6 show even the higher speed to be less than that of light, it must be postulated that either the constants are not chosen so as to represent natural conditions or that from this faster wave another one separates traveling faster yet, namely, at the speed of light.

As to the fallacies in the way of choosing constants, it may be pointed out that, contrary to the assumption on p. 879 of Mr. Bewley's paper, an isolated wire in the field of another one does not necessarily form corona corresponding to its potential in this electrostatic field. It should be remembered that, however high its potential, this wire is in a field of lower intensity than the critical corona gradient as long as this wire is outside of the corona envelope of the first one. A cylinder of any diameter in a homogeneous field simply raises the maximum field strength at its surface to twice that of the original field. This alone determines whether or not there is initially any corona on the secondary wire.

At any rate, Bewley's analysis gives the key to the full understanding of most traveling wave phenomena laid down in oscillographic records. Especially, the sensible evaluation of attenuation data is now possible since almost all records of waves accompanied by parallel conductors clearly indicate the separation in 2 principal components each of which can be analyzed separately sufficiently well by means of an exponential attenuation law. In this connection it may be suggested that we work toward the adoption of a system of attenuation constants which is both logical and convenient for practical use. The fundamental terms could be of the form

$$e = E_n \times \epsilon^{\frac{-x \cdot 0.69}{K_n}}$$

or somewhat similar where x is the distance travelled and K_n the distance in which the wave component E_n drops off to half voltage due to its particular attenuation characteristics. In adding the different components one must remember that they travel at different speed which now explains to the greatest part why these constants have varied so widely when derived from actual observations without this important new consideration. They ranged about as follows:

Due to Corona.
1 to 6 miles for attenuation to half value.

Due to Resistance.
10 to 25 miles for attenuation to half value.

C. L. Fortescue: L. V. Bewley has presented the A.I.E.E. with a very interesting and stimulating paper. Largely on account of its stimulating character, I think this paper is the best one that Mr. Bewley has contributed to the Institute.

There is no question in my mind as to the superiority of Mr. Bewley's method over the previous approximate methods where in both cases true attenuation is ignored. Mr. Bewley's paper will, therefore, be of great value to electrical engineers. In the past few years I have given much thought to obtaining approximate solutions of wave problems satisfactory for practical purposes. Such solutions are naturally partly empirical as is the case with many of our engineering solutions. Mr. Bewley's theory will eliminate a large part of this empiricism.

Dr. Slepian has shown in his discussion of Mr. Bewley's paper why Mr. Bewley's equations and the solutions he derives are really incompatible. This is easily visualized by considering a charge on an infinite wire having a perpendicular field constrained in some manner to move with a velocity v less than the velocity of light. The motion of this charge will be at once to create a magnetic field in space and the changes set up will be propagated with the velocity of light. The potential of the line ahead of the moving charge at the start of the motion will be zero, but with the motion a change will take place at the conductor surface and parallel component of electric force will appear so that the electric force will be no longer perpendicular. In other words, energy will be transferred from the slowly moving charge to the portion of line in front of it creating a wave which will move with the velocity of light. In short, a wave on a wire in air in the presence of a perfectly conducting earth plane will move with the velocity of light whether corona be present or not. The distortion of the wave, however, should be capable of representation by considering the wave to be made up of several waves moving at velocities less than that of light and one wave having the velocity of light. This could be done by considering a component of current to exist in the corona envelope parallel to the line due to the fact that at the front of the wave the direction of ionization is not radial to the line when corona is present but at an angle thereto.

It is certainly true that the electrons moving in the direction of the radial field will be subjected to a force parallel to the conductor in the direction of motion of the wave on the wire. Whether the component of current due to this force will be of sufficient magnitude to noticeably affect the velocity of propagation of the wave is open to question.

Let us now consider the penetration in the earth. At the surface of the conductor there exist 2 types of current, namely, conduction current in a direction parallel to the conductor and displacement current usually taken as being at right angles to the surface of the conductor. When the earth is represented by an infinite perfectly conducting plane, a similar charge distribution of opposite sign will exist on the surface of the earth provided the wave on the wire is traveling with the velocity of light and this charge distribution and corresponding conduction and displacement can be properly represented by the image of the wire with its wave considering the surface of the earth as a perfectly plane mirror.

In the case where the earth is represented by a semi-infinite dielectric having dielectric constant K and where q is the charge per unit length of the conductor, accepting Mr. Bewley's perpendicular field, this field in the air may be obtained by assuming a charge q' less than q at the optical image of the conductor in the dividing plane between the air and the dielectric. The field in the dielectric will be given by q'' an imaginary charge distribution on the conductor. The values of q' and q'' are given by

$$q' = \frac{K-1}{K+1}q$$

$$q'' = \frac{2K}{K+1}q$$

It will, therefore, be plain that the displacement currents do penetrate the earth to a considerable distance and that the capacities obtained by considering q' as equal to q are much too large. q' can be equal to q only when K becomes infinite, *e. g.*, the earth is a perfect conductor as K diminishes, the field in the air approaches that due to an isolated conductor in space. It will also be quite evident that the surface of the earth considered as a dielectric will not have a potential of zero.

When the conductivity of the earth is low, it is probable that its dielectric constant K will have a preponderating influence in determining the current and field distribution. Both displacement currents and conductive currents will be present in the earth. The distribution and depth of penetration will probably be somewhere between that determined for a perfect conducting earth and that determined by considering K alone. I think that any penetration into the earth of conduction or displacement currents will have the effect of slowing up the waves of the wires by energy and actual attenuation. Moreover, it is possible that the velocity of propagation is not uniform but decreases with time and distance traveled.

What I wish particularly to emphasize in the above discussion is that the current is a solenoidal vector and that the electromagnetic and the electric fields are inextricably tied together by this fact so that the so-called zero potential plane or planes are determined by the distribution of current in the earth. In only one case does this plane lie at the surface of the earth and this is when the resistivity of the earth is zero.

Mr. Bewley's theory indicates that the presence of ground wires will greatly increase the attenuation of waves above corona traveling over the line wires. If this is true it is an important addition to our knowledge of traveling surges, and it furnishes another advantage in favor of ground wires, for apparatus has little to fear from traveling waves below the corona point. If a ground wire system has a high enough protective level so that flashover due to a lightning stroke cannot occur, the traveling wave that appears on the line wires will be very small as the positive and negative traveling waves induced by the corona on the ground wires do not have time to separate appreciably and the portions that are in phase tend to cancel each other, the net result is a wave of low magnitude having both negative and positive parts. This is indicated by cathode ray oscillograph waves that were obtained at the Roseland substation during lightning storms in the summer of 1930.

If I am not mistaken Mr. Bewley's theory provides the missing factors which have been baffling us during the past few years and furnishes the answer to the apparent high coupling factors that result when corona is present as a result of a lightning stroke to line or tower. The coupling factors are actually less but this is more than compensated for by the energy transfer from the ground wire to the line which after a fraction of a micro-second begins to decrease the amplitude of the wave on the ground wires and increase the amplitude of the potential on the line wires. At the crest of the wave a considerable reduction has been affected in the difference of potential between line and ground wires. Apparently this difference of potential will increase more abruptly but the crest and tail of the difference of potential wave will be considerably reduced.

To summarize, I think that a factor is missing in Mr. Bewley's equation which should bring in a wave of small magnitude traveling with the velocity of light. Tests have been made by us on velocities of waves below the corona point and the velocity of the front agrees with that of light within the probable errors of measurement. Corona does not take place at the front of the wave and in fact a corona time lag is probable so that a considerable portion of the front has passed a given point before corona begins to form at this point. There appears to be no valid theoretical reason for assuming that the discontinuity at the front of a wave having corona does not travel with the velocity of light.

In conclusion, I wish to congratulate Mr. Bewley on this paper which presents a theory which is a big step in advance of the past generally accepted theories of wave propagation under corona conditions. The defects which appear to me to be present in his physical interpretations are not pointed out in the spirit of criticism but in the hope that further analytical research may show the way to remove these defects and arrive at a still better interpretation of the problem of wave propagation over wires.

Appendix to Discussion

I prefer to express Mr. Bewley's equations in a little different form from those he uses. For simplicity consider the 2-conductor problem. The first 2 equations are the same as his, the next 2 are the reciprocal equations to his. The system of equations then becomes

$$\left.\begin{aligned}
-\frac{de_1}{dx} &= L_{11}\frac{di_1}{dt} + L_{12}\frac{di_2}{dt}\\
-\frac{de_2}{dx} &= L_{21}\frac{di_1}{dt} + L_{22}\frac{di_2}{dt}\\
-\frac{1}{C^2}\frac{de_1}{dt} &= L_{11}'\frac{di_1}{dx} + L_{12}'\frac{di_2}{dx}\\
-\frac{1}{C^2}\frac{de_2}{dt} &= L_{21}'\frac{di_1}{dx} + L_{22}'\frac{di_2}{dx}
\end{aligned}\right\} \quad (1)$$

where C is the velocity of light and the inductances may be expressed in practical or absolute units. By differentiating the first 2 equations with respect to x and the second 2 with respect to t, we obtain 4 equations re-

lating $\frac{d^2e_1}{dx^2}$ and $\frac{d^2e_2}{dt^2}$ to $\frac{d^2i_1}{dx\,dt}$ and $\frac{d^2i_2}{dx\,dt}$ eliminating $\frac{d^2i_1}{dx\,dt}$ and $\frac{d^2i_2}{dx\,dt}$. From these 4 equations we obtain 2 linear equations relating $\frac{d^2e_1}{dx^2}$ and $\frac{d^2e_2}{dx^2}$ to $\frac{d^2e_1}{dt^2}$ are $\frac{d^2e_1}{dt^2}$. Obviously the rest of the solution will proceed along the same lines as Mr. Bewley's solution. If $L_{11}' = L_{11}$ and $L_{12}' = L_{12}$, eq 1 shows that

$$\frac{1}{C^2}\frac{d^2e_1}{dt^2} = \frac{d^2e_1}{dx^2}$$

and

$$\frac{1}{C^2}\frac{d^2e_2}{dt^2} = \frac{d^2e_2}{dx^2}$$

the ordinary equations of propagation of waves along wires with the velocity of light.

L. V. Bewley: Prof. A. R. Miller gives a somewhat different method of analysis for the 2-conductor system, and calls attention to the pair of waves moving in the other direction. In Appendix I of the paper I was interested merely in the forward waves, and therefore, did not explicitly specify the backward waves. But in the general solution given in Appendix II for any number of conductors the complete system of forward and backward waves is explicitly derived. Professor Miller also points out that resistance and leakance are neglected. I gave the differential equations for this case in a previous paper ("Traveling Waves on Transmission Lines," A.I.E.E. TRANS., v. 50, 1931) and repeated it in chap. 6 of my book ("Traveling Waves on Transmission Lines," John Wiley & Sons). However, I confess that I have never carried through a complete solution of these differential equations except in the case of a 2-conductor system. The solutions with losses included are no longer simple traveling waves. I very much doubt the value of calculations based on fixed constants for resistance and leakance; especially since most of the loss is due to corona (a function of the voltage) and the ground resistance (a transient skin-effect problem).

Dr. Slepian admits the existence of multi-velocity waves and agrees that they result from the finite ground resistivity and corona. But he questions the validity of the differential equations from which I arrived at my conclusions. I do not state, as he implies, that the zero-potential plane lies below the ground surface except in the case of a resistive earth. Nor do I claim that "the component systems propagate with only small attenuation and distortion, and at definite velocities which are independent of the wave shape of the component waves." Under *Conclusions* I named and briefly discussed three principal causes of attenuation and distortion, only one of which was the subject of my paper. As far as the velocity depending upon the wave shape is concerned, it is easy to see that for short waves the average depth of current penetration is less than for long waves, and consequently the velocity must be higher. I pointed out this fact on page 74 of the Feb. issue of the *Gen. Elec. Rev.* in an article on "The Counterpoise." Dr. Slepian's theorem concerning multivelocity components agrees perfectly with the conceptions given in my paper, and is, in fact, a description of my Fig. 7. Regarding Mr. Slepian's contention that the differential equations are not valid for waves moving at less than the velocity of light, I can only say that it has long been recognized that they are approximate, and partly for the reasons given by him (which idea was first developed by Sir J. J. Thompson). The question is: how good an approximation are they? The ideal way to answer this question would be to make a complete analysis based on Maxwell's equations. Mathematically this is beyond me. However, I have gone far enough to see that the solution is not a wave solution and the final formulas would be quite complicated. Therefore, from an engineering point of view such an elaboration is not very practical except as a means for establishing the range of validity for the approximate differential equations. The other way out of the difficulty is to do as I did; consider the great lengths of the wave relative to the height of the line and thus infer intuitively that throughout the greater part of the wave length the longitudinal components of the compressed field of each moving electron are mutually cancelled; so that a pure radial field may be assumed except at the front of the wave or where an abrupt jump occurs (end effects). This means that my differential equations are not open to Dr. Slepian's objections except in the neighborhood of an abrupt jump, and for a distance not much greater than a low multiple of the height of the line. For example, if a wave is 30 μsec long and has an abrupt front, and the line height is 50 ft above earth, then for 0.1 μsec or so at the wave front my differential equations are probably poor approximations, but for the other 29.9 μsec of the wave (away from the "end effect") they are probably very good approximations. In any event, they yield a simple solution which agrees with the experimental evidence and suffice to explain the observed phenomena.

Mr. R. D. Evans offers some figures on the effective depth of return for a conductor located 100 ft above the ground surface and for a frequency of 1,000,000 cycles, and finds that the effective depth is different for magnetic than for electric effects. I take it that the figures he gives are distances below the overhead conductor, rather than depths below the ground surface. If this is so, then his figures verify my contention that the ground surface is essentially a zero potential surface with respect to the electrostatic field from overhead conductors. I agree with Mr. Evans that the depth of current penetration in the ground is not so great at the wave front as on the tail. But if this variation is taken into account the analysis becomes unmanageable. If any average depth for the current images is used, then only simple traveling wave components result. I suppose that an analysis of this type, if it is to have much engineering use, must remain simple. Nevertheless, an appreciation of the variable depth of penetration allows us to visualize certain aspects of traveling wave phenomena; for example, the elongation on the tail of short chopped waves. Consider, for instance, a short rectangular wave, which we may think of as the superposition of two displaced infinite rectangular waves of opposite polarity. Let Fig. 8 of my paper indicate the current distribution in the earth of each infinite rectangular component. Superimposing two such patterns of opposite polarity and displaced by distance equal to the length of the chopped wave, clearly shows how the tail of the wave will be built up, the front rounded off, and the crest reduced. A sketch made in this fashion shows a striking similarity to the distortion experienced by chopped waves.

Mr. Otto Ackermann suggests that the calculations given in Table I of the paper which show the fast velocity less than that of light, are either based on incompatible assumed constants or else there is a third wave present moving at the velocity of light. I believe the latter to be right, as I will try to show in answering Dr. Fortescue's discussion. Mr. Ackermann points out that an isolated wire in the field of another wire does not necessarily form corona corresponding to its pontential in this field. He is quite right, and one should compute the gradient taking cognizance of the fact that a cylindrical wire immersed in a uniform field doubles the intensity. Regarding a workable attenuation formula, exponential terms certainly have the advantage of easy manipulation in mathematical formulas, as well as being simple and compact. For estimating purposes I have found the Foust and Menger empirical formula of great help, particularly concerning questions of station outages.

Dr. C. L. Fortescue, as well as Dr. Slepian and Mr. Ackermann, argues for a wave component traveling at the velocity of light. There is no doubt in my mind that there is such a component present, but I believe that it is small compared with the components which I calculated. This velocity-of-light component is due to the electromagnetic field sweeping ahead of the main surge. Sir J. J. Thompson, O. Heaviside, and many others have shown by means of Maxwell's equations that an isolated electron (or spherical charge) suddenly set in motion at a velocity less than that of light will give birth to a spherical wave propagating at the velocity of light. Now, if this single charge happens to be guided by an isolated wire, then the associated electromagnetic field will induce in that wire a potential traveling at the velocity of light. If there is an adjacent wire the field will induce in it a potential *of the same polarity.* This is contrary to the observed polarity at the front of the induced wave, unless this induced component happens to be so small that it is lost on the oscillograms in comparison with the major wave components. But why should it be so insignificant? I hazard the guess that the proximity of a resistive earth carrying the approximate image of the advancing charge on the overhead conductors also has a velocity-of-light electromagnetic field which being essentially equal and of opposite sign to that of the charge on the line, practically nullifies the field ahead of the advancing surge at a distance equal to a few times the height of the line. Therefore, the amplitude of the velocity-of-light component on the overhead conductors decreases rapidly and at short distances ahead of the advancing main surge ceases to be apparent. Regarding a permittivity constant K for the earth, I am a bit dubious. I believe that the conductivity of the earth is always sufficient so that displacement currents in the earth may be ignored a hundred feet or so behind a wave discontinuity. But I

hope to know more about this point later on.

The wholesome and constructive criticism on my paper is most gratifying to me. I appreciate fully that the theory which I presented is merely a stepping stone toward, I hope, a better understanding of traveling wave phenomena.

Counterpoises for Transmission Lines

Discussion of a paper by Charles L. G. Fortescue published in the December 1933 issue, p. 908–17, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 467–80.

J. P. McKearin: The 115-kv and 66-kv system of the Turners Falls Power and Electric Company, one of the constituent companies of the Western Massachusetts Companies, extends throughout the western part of Massachusetts connecting Turners Falls, Pittsfield, Springfield, and Hartford, with taps to most of the intervening towns and cities. This system is connected at 115 kv with the New England Power Company's system and at 66 kv with the system of the Hartford Electric Light Company at Hartford.

Three years ago a program of improvement in protection against lightning was started and Table I shows the indicated results up to the present time, as well as the detailed changes made. (See also Figs. 1, 2, and 3.)

The most outstanding example of improved protection against lightning on this system is the 33.1-mile 66-kv interconnecting line between Agawam and Hartford. Comparing the 6-year record before, with the 3-year record after improving its protection against lightning, flashovers due to lightning have been reduced 95 per cent.

There have been 3 lightning flashovers since it was reinsulated in the spring of 1931. Of these 3, one was on a river crossing tower so high that it could not be protected. There is a short tap line, $3^2/_3$ miles long, of the old unprotected type of construction, connected to the Hartford line, and one of the other 2 lightning flashovers may have occurred on this tap line.

The record on the 36.7-mile 115-kv line from Cabot to Pittsfield shows a good improvement against lightning flashovers, but the improvement is not as great as that on the Hartford line. The reduction in light-

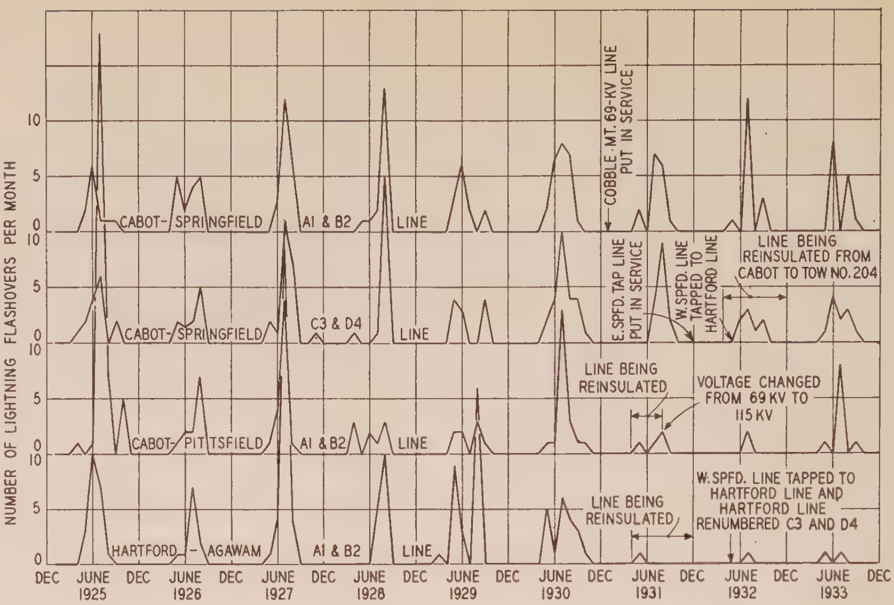


Fig. 1. Lightning flashovers per month on Turners Falls Power and Electric Company's 66-kv and 115-kv transmission lines

All tap lines are included. Entire Hartford-Agawam line is included. West Springfield and Margaret Street lines are included as part of Cabot-Springfield C3 and D4 lines until tapped to the Hartford line. The E5 line is not included

In Figs. 1, 2, and 3, a flashover is taken as one flashover regardless of whether or not it flashes over one or both circuits of a double circuit line

Table I—Lightning Protection of Western Massachusetts Companies Transmission Lines

	Agawam to Hartford C3 and D4		Cabot to Pittsfield A1 and B2		Cabot to Agawam C3 and D4		Cabot to Agawam A1 and B2
	Before Reinsulation	After Reinsulation	Before Reinsulation	After Reinsulation	Before Reinsulation	After Reinsulation	
Line kv	66	66	66	115	66	66	66
Miles of line (exclusive of taps)	33.1	33.1	36.7	36.7	39.8	39.8	48.7
Miles reinsulated		33.1	....	36.7	....	18.8	None
Lightning F.O. per yr (6 to 9 yr avg)	22.3	....	20.2	....	16.4	....	16.4
Lightning F.O. per yr (3 yr avg)		1.0	....	5.3*	....	....	....
Lightning F.O. per yr (2 yr avg)		....	....	....	....	9.5	....
Size of insulators in inches	5 × 10	5 × 10	$5^3/_8$ × 10	$5^3/_8$ × 10	$5^3/_8$ × 10	$5^3/_4$ × 10	$5^3/_8$ × 10
No. of insulators in string	5 and 6	9 and 10	6 and 8	9 and 10	4 and 5	8 and 9	4 and 5
Type of gap	None	Ring	Horn	Horn	Horn	Ring	Horn
Gap length in inches		39 and 44	$24^1/_8$ and $32^7/_8$	$36^1/_4$ and $43^5/_8$	$15^3/_8$ and $20^3/_4$	40 and $45^3/_4$	$15^3/_8$ and $20^3/_4$
% of line having counterpoise	None	60%	None	87%	None	33%	27%
Type of counterpoise		$^3/_8$" steel	....	1/0 Cu.	....	1/0 Cu.	1/0 Cu.
No. of overhead ground wires	1	2	1	1	1	1	1
Type of overhead ground wires	$^3/_8$" steel	$^3/_8$" steel and ACSR	$^3/_8$" steel	$^3/_8$" steel	$^3/_8$" steel	$^3/_8$" steel	$^3/_8$" steel
Phase conductors	4/0 ACSR	4/0 ACSR	2/0 Cu.	2/0 Cu.	1/0 and 2/0 Cu.	1/0 and 2/0 Cu.	1/0 Cu.
Phase spacing in ft (vertical)	10	10	10	10	9 and 10	9 and 10	8, 9, and 10
Average length of span in ft	564	564	584	584	512	512	533
Approx. height bottom conductor in ft	45	45	45	45	45	45	45
% of footing resist. over 20 ohms before counterpoise was installed	45%	....	....	....	....	....	....

*There have been 16 lightning flashovers on this line during the 3 years since it was reinsulated. Seven of these flashovers occurred within a period of 23 min, July 21, 1933, during one of the most severe lightning, wind, and rain storms experienced in this territory.

ning flashovers is 74 per cent. However, the Pittsfield line does not have as much protection as the Hartford line. It has only one overhead ground wire, carries a little less insulation, and has an exposed route over the Berkshire Mountains. The route of the Hartford line is down the valley of the Connecticut River.

The 39.8-mile 66-kv line from Cabot to Agawam has been reinsulated for about $^1/_2$ its length and its lightning flashovers have been reduced 42 per cent.

The 48.7-mile 66-kv line from Cabot to Agawam, has not been reinsulated and there has been no significant change in its number of lightning flashovers per year. This would indicate that the reduction in lightning flashovers obtained on the other lines has been due principally to the increased protection against lightning rather than to a reduction in the severity of the lightning storms to which they have been exposed.

C. L. Fortescue: In reply to the general discussion of my paper, I wish first of all to disclaim any intention on my part to present a complete analytical theory of counterpoise action. In the first place, a thorough analysis of this complicated problem presents extreme difficulties and would not be justified on account of our meagre knowledge at present of so many of the factors that enter into the problem. In the second place, it is my opinion that only a fair approximation to the solution of the problem is necessary and that closer approximation, even if our knowledge of lightning phenomena made it possible, would not be justified if it entailed the very great complications that the complexity of the problem seems to indicate. Therefore, it seemed to me that an approximate semi-empirical method based on the actions in a homogeneous medium which could be adapted to the requirements of the increased statistical knowledge of these actions in the course of time would prove satisfactory. I suppose no one is more fully aware of the shortcomings of his paper than the author himself, but in the present paper I feel that I have quite frankly told my readers that the method outlined while it explains the operations of counterpoises approximately on the basis of our present statistical knowledge may need revision from time to time as our knowledge increases.

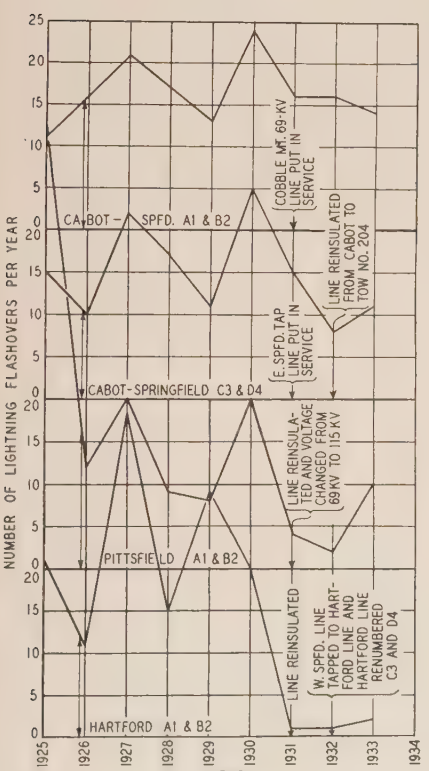


Fig. 2. Lightning flashovers per year on Turners Falls Power and Electric Company's 66-kv and 115-kv transmission lines

All tap lines are included. The Hartford line is included. The E5 line is not included. The West Springfield and Margaret Street lines are included with the Cabot-Springfield C3 and D4 line until tapped to the Hartford line

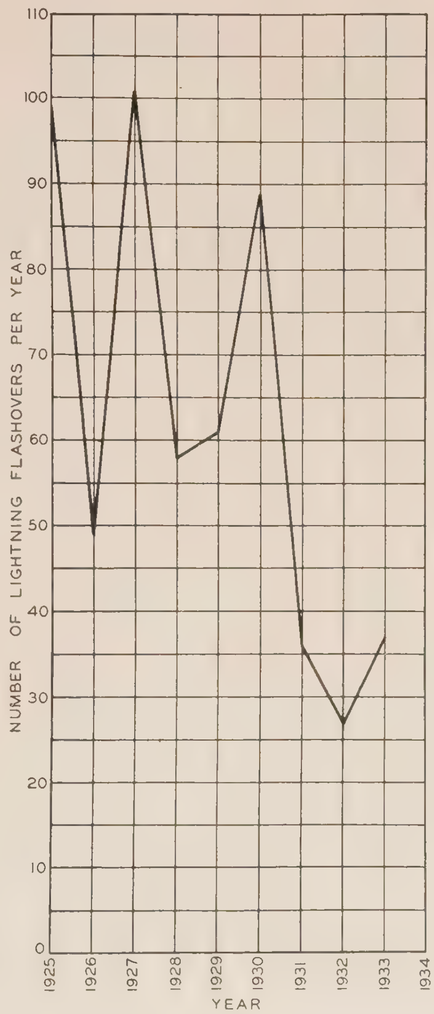


Fig. 3. Lightning flashovers per year on the Turners Falls Power and Electric Company's 66-kv and 115-kv transmission system

The entire Hartford-Agawam line is included. The E5 line is not included. Otherwise all the company's lines and taps are included

Considering Mr. Bewley's discussion in more detail, I cannot subscribe to Mr. Bewley's assumption that the ground plane for the electric field is at or near the earth's surface when the resistivity of the soil is high. I have discussed this matter in connection with Mr. Bewley's paper presented at this present session and will refer those interested to my discussion. This will account to a great extent for the difference between Mr. Bewley's numerical results and my own.

Regarding Mr. Bewley's views as to the proper value to ascribe to the surge impedance of the lightning stroke, I wish to point out that the value of 200 ohms which I have used has been applied to the analysis of a great number of existing lines on which there is reliable statistical data and seems to accord very well with this data. It also appears to be consistent with value of surge current in towers that have been recorded during the past few years and the maximum values of surge potential that have been measured on well insulated lines. However, it should be pointed out that this surge impedance cannot be considered constant over the whole length of the lightning channel and it seems reasonable to suppose that where the ground plane is a great distance below the surface of the earth there may be an increase in the value of the surge impedance of the lightning channel where it strikes a transmission line.

With regard to the high coupling factors obtained in my numerical calculations, this can be remedied in 2 ways, (1) by changing the value of S used in the numerical calculations, and (2) by decreasing the depth of the ground plane. By using a larger value of K (which may be justified) and a smaller value of S, the same protection level will be obtained numerically. The numerical results seem to accord well with the results obtained by the single counterpoise over High Knob. Whether these results should be obtained numerically by decreasing the depth of the ground plane using higher values of K and changing the values of S or by any other combination permitted by the method and the physical characteristics of the location is a matter of judgment. I am personally convinced that Mr. Bewley's value of 0.44 is much too low and applies more nearly to a case where the resistivity of the soil is fairly low and the ground plane is at a depth of 50 ft. Referring to Mr. Bewley's remarks that the numerical work was carried out in too much detail, I may say that this was intentional and was done to show that the actual wave of impressed voltage diminished very rapidly to about one-half value in 3 μsec. I have developed a shortcut method which has not been published by which the solution can be obtained approximately in about $^1/_5$ the time required for the detailed calculation given in the paper. This method checks with the longer method within 5 per cent.

With regard to the supposed geometric mean radius used in my calculations, the term geometric mean radius used is a misnomer. The method actually used is

the same as that given by Mr. Bewley, the detailed calculations were omitted as being of no particular interest. An inadvertent omission was made in the calculations which Mr. Bewley points out in (5) of his discussion, but which does not materially change the final results.

Mr. G. P. McKearin's discussion is extremely interesting and furnishes important data regarding the performance of counterpoises. I have no data regarding the resistivity of the soil in the territory over which the lines he refers to pass or to put it another way, the average normal tower footing encountered along the right-of-way of the line, but I believe that in New England these values will generally be high. From this standpoint the greater part of the reduction in outages of the Agawan to Hartford line may be credited to the counterpoise. In the case of the Cabot to Pittsfield section of the line the larger share of the outages of the finally insulated line may be directly credited to imperfect shielding against which there is no effective measures for protection. It seems reasonable to ascribe 3 to 4 of the outages per year of this line to imperfect shielding. While the effectiveness of the counterpoise would have been more positively shown had the Cabot to Agawan A_1 and B_2 been insulated with 9 and 10 insulators, I think that Mr. McKearin's paper furnishes invaluable data in connection with the studies of the protective effect of counterpoises. It is to be hoped that he will follow this up with further records in future years and that others will be encouraged to install counterpoises on lines which are showing poor performance against lightning, so that more statistical data will be available.

Referring to the discussion of Mr. Cozzens, he has apparently misinterpreted my general comments on counterpoises. In my paper the idea of crowfoot or radial versus parallel counterpoises was discarded entirely and I pointed out that all counterpoises may be considered as composed of parallel and cross counterpoises, the former being parallel to the transmission line and the latter at right angles. Under the same conditions the parallel counterpoise and the cross counterpoise have the same surge impedance but the parallel counterpoise will not be so effective in lowering the potential of the transmission system due to its surge impedance on account of its mutual surge impedance with the overhead ground wires. It follows naturally that if this mutual surge impedance is zero or negligible there is no particular merit for the parallel counterpoise over the cross counterpoise except its continuity eliminates the possible ill effects of end reflections. In considering the surge impedance of wires leaving the tower footing in opposite direction, I have used the simple expedient of considering them as being in multiple without mutual surge impedance. I believe this approximation is all that is justified from a practical standpoint. There are some differences from my viewpoint in the fundamental conception of the problem in Mr. Cozzens' discussion which I am not prepared to discuss at the present time and which perhaps will be clarified with increased statistical knowledge of the problem.

Referring to Mr. Hertz's discussion, I wish to supplement it by remarking that when two or more ground wires or counterpoise wires are used a variation in the diameter of these wires over rather wide limits has little effect on the electrical characteristics. From an electrical standpoint, it apparently makes little difference what material is used for the overhead wires. The main requirements are that they shall have ample mechanical strength and shall be capable of withstanding the weather conditions without corrosion and be capable of withstanding the most severe direct stroke of lightning without being sensibly weakened by pitting. Since the breaking of a ground wire would probably cause as much disturbance to service continuity as the breakage of a line wire, a large factor of safety should be used in the ground wire construction.

Herman P. Miller, Jr., has kindly given the viewpoints of a radio engineer in his discussion of which I wish to express my appreciation. Some of the ideas he expresses have been already incorporated in our ground wire theory, particularly in connection with the effect of the tower on the potential of the system after being struck by lightning. The calculations are usually carried out by the method of reflections which, of course, is another way of saying that the natural period of the various elements is taken into account. The ideas expressed by Mr. Miller are worthy of careful consideration.

Replying to the discussion by P. B. Stewart and F. E. Sanford, I wish to say, although I have not read the article by N. Bogoiavlensky that I am rather skeptical as regards radio activity having any substantial effect on the frequency of thunderstorms. The effect of pointed profiles may be just as easily explained by the simple phenomenon of the wind currents being deflected upwards. Of course, we know that in many localities the isoceraunic level is much higher than the average as represented in the Government's isoceraunic map of the country. The topography of those localities will generally explain the reason but the frequency of thunderstorms has nothing to do with the design of a transmission line for a particular protective level. This is purely a matter of electrophysics. The problem of outages on the transmission line is a matter of protective level and probability based on the isoceraunic level of the territory through which the line passes. Naturally if a certain line performance is desired (outages per 100 miles per yr) where the isoceraunic level is high the line must be designed for a higher protection level whether it happens to be a 115 kv line or a 230 kv line. I have yet to find a case where the principles of ground wire protection properly carried out have not produced expected results. One of the principal troubles I have encountered in teaching the theory of ground wire protection is to get engineers to see the importance of adequate shielding. To be adequate, shielding must be practically 100 per cent. Another is the tendency of engineers to apply a voltage classification to transmission lines. Thus a 132 kv line is supposed to require 9 or 10 suspension insulators in a string. This is frequently stuck to whether the isoceraunic level is exceedingly high or not. There is no reason why if the 132 kv line is important enough it should not be insulated with 12 insulators or 14 if found necessary.

Corona Losses From Conductors of 1.4-In. Diameter

Discussion of a paper by Joseph S. Carroll, Bradley Cozzens, and Theo. M. Blakeslee, published in the December 1933 issue, p. 854–60, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 470–1.

T. F. Peterson: I hesitate to offer a discussion on this paper without first commenting on the stupendous nature of the work undertaken at the Stanford University laboratories. There are very few places where loss measurements could be made on conductors designed for such high voltage operation, and erected with normal line spacing and insulation. There is small wonder, then, that all conceivable variables have not been introduced into the work. The length of time available for the testing would certainly have militated against this, even if all types of conditions could have been created.

Personally, I feel that the authors have done a very valuable piece of work (even if only for academic reasons) in so clearly presenting the influence of grease coatings on the total corona loss. This may be viewed as due to dielectric loss in the dielectric (grease) interposed in the electric circuit. I think it should be of interest to note that similar phenomena have been observed at Massachusetts Institute of Technology where power factor increase of nominally "zero" loss condensers has been attributed to oxidation of surfaces.

It seems obvious that losses due to grease films will diminish with time and weathering. The authors point out that corona loss may be modified by bird deposits. Certainly normal weathering will cause some changes. In view of this, is it economical to clean conductors? Since we are concerned with the capitalization of losses over a long period, is it justifiable to put too much weight on loss measurements made under ideal conditions? In reality the losses are almost the same for all conductors for voltages considerably in excess of the operating value. Real differences are brought out only at very high voltages. In this range the curves are easily shifted by change in surface conditions and, for similar surface treatment or time of weathering, the percentage shifts may vary considerably depending on designs. Is it not quite possible, therefore, that mechanical features are far more important than any differences brought out in the paper?

For the benefit of one of the previous discussors, who raised the question of rain loss, may I point out that work in which I took part about 10 years ago (see "Power Measurements at High Voltages and Low Power Factors," by J. S. Carroll, T. F. Peterson, and G. R. Stray, A.I.E.E. TRANS., v. 43, 1924, p. 1130–8) indicated that, although relatively smooth surfaced, locked wire conductors showed lower clear weather losses than stranded conductors of like size; the former developed a much greater percentage increase in loss during rain. I don't know whether this could be attributed to the fact

that each drop of water on a smooth surface caused a greater loss than on stranded surface, or whether the frequency of appearance of drops along the conductors was such as to produce results. As a matter of passing interest it might be pointed out that design F had a radius of curvature of each segment less than the radius of the conductor in order to "submerge" the edges and also to create a scalloped effect designed to approach "ordinary strand" rain characteristics.

T. J. Little and L. F. Hickernell: The data presented in the paper are very interesting from an academic point of view and represent a valuable contribution in the study of corona loss. It is believed, however, that certain of the conclusions warrant some discussion.

Conclusion 1 states that "The importance of the die grease as affecting corona loss was further emphasized by the 1933 tests."

It is assumed that the *degree* of importance assigned to this condition applies principally to the accuracy of the results obtained in the laboratory.

Conclusion 2 states that "Complete grease removal either by thoroughly washing, or by washing in connection with a period of aging, is necessary to obtain consistent corona loss data."

It is again assumed that this applies directly to laboratory test results since the authors have shown in their previous paper (A.I.E.E. TRANS., v. 52, 1933, p. 58, Fig. 5) that cable which had aged 7 months showed lower corona losses than at its initial washed condition.

Conclusion 3 states that "Both gasoline and soap and water washings are necessary to accomplish complete cleaning of the cables."

Presumably this applies to the conditioning of samples for laboratory tests. Cases have been brought to our attention where radio interference (a measure of corona loss), noticeable upon erection of the line, has practically vanished after the first few months of operation as a result of the aging of the conductor.

Conclusion 4 states that "Rain greatly increases the corona loss from conductors, but there appears to be little correlation between loss and rainfall rate."

Of more importance than the correlation between loss and rate of rainfall would be a comparison of the loss during stormy weather among the several types of cable constructions. It is to be regretted that the investigation was not extended to include comparable data during stormy weather on *all* of the samples submitted.

Conclusion 5 states that "While the differences in the corona loss for separate types of 1.4-in. stranded conductors are slight, the tests indicate that the size of the outside strands and the neatness of the stranding are factors affecting corona."

It is quite generally accepted that the smaller the size of strand, the lower the loss and neatness of stranding naturally tends toward a more uniform surface.

Conclusion 6 states that "Smooth, properly formed segment conductors have a lower corona loss than stranded conductors of the same diameter."

Reference to Fig. 13 shows very slight difference in losses in the operating voltage range and these losses would undoubtedly be reduced after aging to a value of small or no economic importance.

Reference to Fig. 13 also shows that Type F (a segmental conductor) has higher losses than Type B (a stranded conductor) which emphasizes *Conclusion 7* stating that "The smoothness of the segments is of prime importance in eliminating loss from a segment type of conductor."

Power Limits of 220-Kv Transmission Lines

Discussion of a paper by Alex A. Kroneberg and Mabel Macferran published in the November 1933 issue, p. 758–66, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 473–5.

R. C. Bergvall: The effectiveness of series stabilizing resistance in preventing pull-out during the transient condition was checked on a 100-kva system but space limitations did not enable me to present the detailed test data in my January 1931 paper. The tests checked calculations very closely and on the particular system tested, over 50 per cent additional power could be delivered by its use without loss of synchronism during severe faults, which increase is of the order of magnitude calculated by the authors.

The former transient power limitations have been removed to such an extent by the various methods proposed that in the future consideration will have to be given toward obtaining a proper balance between the machine and system characteristics that control the transient and steady state limits.

Present methods of calculation have been checked by experience to a sufficient extent that system performance with the series stabilizing resistance can be determined with assurance, and if desired a further check could be made on properly portioned miniature systems now available.

A. A. Kroneberg: No final decision has been made in regard to the design of the Boulder Dam transmission system for the Southern California Edison Company, Ltd.

We are fortunate in Southern California in that lightning is responsible for a very small percentage of short circuits and faults. Therefore a lightning proof line is not a solution of the transient stability problem.

The problem presented by S. M. Zubair can be solved with integraph curves if the following modifications are performed. Equation 8 of appendix IV when expanded becomes

$$R \sin \delta + S \cos \delta - E = - J$$

where

$$R = \frac{E_1 E_2}{Z_{12}} \cos \alpha_{12}$$

$$S = \frac{M_1 - M_2}{M_1 + M_2} \frac{E_1 E_2}{Z_{12}} \sin \alpha_{12}$$

$$E = \frac{M_2(P_1 - P_{11}) + M_1(P_{22} - P_2)}{M_1 + M_2}$$

$$J = \frac{M_1 M_2}{2\pi f(M_1 + M_2)}$$

This equation is further modified

$$B \sin (\delta + \beta_1) - E = - J \frac{d^2\delta}{dt^2}$$

where

$$B = \sqrt{R^2 + S^2}$$

$$\beta_1 = \tan^{-1} \frac{S}{R}$$

Then (introducing new variables)

$$\psi = \delta + \beta_1;$$

$$\tau = t \sqrt{\frac{B}{J}};$$

$$\frac{d^2\psi}{d\tau^2} + \sin \psi = \frac{E}{B}$$

which can be solved with integraph curves. It will be necessary, however, to correct the equations of appendix II.

$$A' = \int_{\delta_0}^{\delta_1} E d\delta - \int_{\delta}^{\delta_1} B \sin (\delta + \beta_1) d\delta$$

$$A'' = \int_{\delta_1}^{\delta_2} C \sin (\delta + \beta_2) d\delta - \int_{\delta_1}^{\delta_2} F d\delta$$

also

$$\psi_0 = \delta_0 + \beta_1$$

$$\psi_1 = \delta_1 + \beta_1$$

The constructive criticism and suggestions appearing in the discussions are accepted by the authors with thanks.

Power Limits of Synchronous Machines

Discussion of a paper by Edith Clarke and R. G. Lorraine published in the December 1933 issue, p. 780–7, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 475–7.

Edith Clarke and R. G. Lorraine: We agree with H. L. Hazen that steady-state stability is fundamentally a dynamic problem. Nevertheless, it differs from transient stability in that the disturbance (whether an increment of load or a change in angle) is slowly rather than suddenly applied. Consequently, when an increment of load is applied, there is a slow change in the angular positions of the machines of the system until they reach new positions of stability or lose synchronism. During these slow changes the electrical torque is determined by the synchronous reactances of the machines.

In accordance with the usual assumption of constant field currents during a test for steady state stability, the action of voltage regulators is neglected. We have assumed for the multimachine system that one generator only supplies the additional in-

crement of power required. Although it is not so stated in the paper, this is equivalent to the assumption that this generator is equipped with automatic frequency control, while all other machines whether generators, motors, or condensers, have fixed mechanical loads. Under this assumption, if the system is to remain in equilibrium under steady conditions and normal frequency, these "other machines" must take up angular positions such that their electrical power is equal to their mechanical power, and since their mechanical load is constant they will of necessity be fixed power machines.

Professor Dahl has discussed the advisability of assuming all other machines fixed in phase with respect to each other when an increment of load is added to one machine of the system. For the general case this can be true only in the first instant after an increment of load is suddenly applied.

In the case of a generator supplying power over a long transmission line to a load center, the assumption of constant phase angles between the machines in the load area will, as Professors Dahl and Hazen both point out, give a fair approximation to the truth. The assumption that the machines in a group remain fixed in phase with each other is equivalent to replacing the group by a single equivalent synchronous machine (see Appendix III). The given system is, in effect, reduced to a two-machine system. The error in treating the system as a two-machine problem will be small when the combined impedance of the generator, transformers, and line (or lines) is large relative to the equivalent load impedance; but when this is not the case, the error may be large.

We are heartily in sympathy with Professor Dahl's statement that agreement in these matters is important. The tests he contemplates making should be of considerable value in evaluating the various factors involved.

The idea of fixed power machines follows directly from the assumption of automatic frequency control on the generator which is being tested. This assumption will, we believe, give a lower stability limit than would be obtained if the required increment of load were supplied by more than one machine. In developing a criterion and in making simplifying assumptions we have endeavored to obtain stability limits which will never be higher than those which will be obtained in actual practice by gradually increasing the system load until synchronism is lost.

For systems in which maximum power occurs on the motor before it does on the generator as the angle between generator and motor increases with the addition of load in the test for stability, our criterion will give satisfactory results. For systems in which maximum power occurs on the generator before it does on the motor, stability limits obtained by our method may be too low.

Mr. Crary in his discussion has explained why this is so for two machine systems. For the 2-machine problem with a shunt impedance load he gives the criterion for stability that

$$-\frac{dP_2}{d\delta_{12}}\frac{1}{H_2} \text{ must be greater than } -\frac{dP_1}{d\delta_{12}}\frac{1}{H_1}.$$

We agree with this criterion and advocate its use for 2-machine systems in which maximum power occurs on the generator before it does on the motor. A system of this type would be a generator supplying power to a shunt impedance load over a transmission line with a condenser at the receiving end.

We would point out that Mr. Crary in his discussion and in the subtitles under his figures gives conditions which are not necessarily sufficient. For example, in Fig. 4(a) the system is unstable because

$$-\frac{dP_2}{d\delta_{12}}\frac{1}{H_2} \text{ is less than } -\frac{dP_1}{d\delta_{12}}\frac{1}{H_1}.$$

It will not necessarily be unstable when $H_2 > H_1$ unless at the same time

$$-\frac{dP_2}{d\delta_{12}} \text{ is less than or equal to } -\frac{dP_1}{d\delta_{12}}.$$

Power Limit of a Transmission System

Discussion of a paper by W. S. Petersen published in the August 1933 issue, p. 569–72, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 477–8.

W. S. Peterson: Due to the fact that the publication of the paper "Power Limit of a Transmission System," by W. S. Petersen, was made without inclusion of the mathematical development, it is well to point out that the calculation of the permissable duration of short circuit as given in the third portion of Table II has some limitations that come from simplifying assumptions. These limitations are not such as to interfere with the great majority of calculations and make themselves evident in items 156 and 157, by producing values greater than unity so that items 158 and 159 cannot be determined.

The items 143 to 161 are to calculate the duration of short circuit after having determined δ_1. It involves a solution of the following integral.

$$t = \frac{1}{\sqrt{4\pi f}}\int_{\delta_0}^{\delta_1}\frac{d\delta}{\sqrt{\mathit{115}\delta + \mathit{95}\sin(\delta + \theta_{Fb}) - \mathit{97}\sin(\delta - \theta_{Fb}) + \mathit{119}}}$$

where the underlined (or italic) numbers are items in the tabulation. This was solved by assuming

$$\theta_{Fb} = \pi/2$$

and a further approximation that

$$\cos\delta = 1 - \frac{\delta^2}{2.3}.$$

For some unusual cases this did not give absolutely perfect results. Where there is doubt about the accuracy, the integral given above can be solved by obtaining the area under a plotted curve between the limits of δ_0 and δ_1.

An Experimental Ignitron Rectifier

Discussion of a paper by L. R. Ludwig, F. A. Maxfield, and A. H. Toepfer published in the January 1934 issue, p. 75–8, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 488–9.

J. J. Linebaugh: The experimental rectifier described by L. R. Ludwig and associates is an interesting and serious attempt to broaden the field of the mercury arc rectifier by raising the efficiency and to improve operation by simplification and reduction of number of arcbacks.

The most radical departure from accepted design seems to be placing the anode and cathode so close together without any mechanical protection from mercury splash and with a direct straight path from cathode to anode. This departure gives a very low arc drop and if feasible from an arcback standpoint, will make the rectifier a direct competitor with the synchronous converter at 220 to 300 volts direct current.

It would be interesting to know if the ignitron rectifiers described were loaded much beyond the amperes mentioned or to destruction, with a brief statement covering their behavior and what parts were affected or destroyed.

I trust this work will be continued, increasing the capacity of the tank and voltage range and report made to the Institute through a paper at some later date.

L. R. Ludwig: The authors were much interested in obtaining the comparative data offered by C. C. Herskind. The comparison which he has made serves very nicely to illustrate the advantages of the ignitron as a rectifier. For approximately the same rating as he has stated, the volume and the arc drop are both considerably less in the case of the ignitron. In answer to his question, we see no reason why the ignitron rectifier cannot be built for higher voltages and higher current ratings than those given in the paper. As a matter of fact, of the particular units mentioned, satisfactory tests have been made up to 600 volts and 600 amperes since the paper was written. The cooling coil in the cathode has given some advantage in reducing the arc drop. Some variations and results have been obtained but a reduction of from one to three volts is customary.

In reply to the question of Mr. Haar, no observation has been made directly as to vibration of the anode stems. It has been found however, that as originally built, they were somewhat light, and at the present time, several detailed improvements in the design have been made, of which this is one.

The authors agree with Mr. Linebaugh in feeling that the ignitron will considerably broaden the field of the mercury arc rectifier. The 6 anode unit described in the paper was tested to destruction. The cathode structure seems quite adequate for currents very much larger than the figures given. Difficulty was obtained with the

anode structures however, principally due to the leads burning at their junction of the shank. Some changes in design have been made to improve these conditions and so far, tests seem quite satisfactory with no destruction under conditions of operation such as the ignitron will be required to fill.

Equivalent Reactance of Synchronous Machines

Discussion of a paper by S. B. Crary, L. A. March, and L. P. Shildneck, published in the January 1934 issue, p. 124–32, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 484–8.

Charles Kingsley, Jr.: In analyzing engineering problems it is frequently helpful to set up an "equivalent" model of the actual circuit or piece of apparatus which we are attempting to analyze. This is the method of attack used in the paper under discussion. The authors set up an "equivalent" unsaturated synchronous machine to serve as a model for the solution of the more complicated saturated machine whose operating characteristics are desired. The particular operating characteristic with which the paper is chiefly concerned is the calculation of the synchronizing power coefficient, $dP/d\delta$.

Whenever we use an "equivalent" model to replace an actual piece of apparatus, we must be sure that the 2 are actually equivalent in all respects which will affect the applicability to the actual piece of apparatus of the results obtained from the analysis of the model. Hence let us compare the actual, saturated synchronous machine with its "equivalent" unsaturated model in order to determine in what respects the 2 are equivalent and where they differ. This may be done more readily for the relatively simple cylindrical rotor machine than for the more complicated salient-pole machine. I shall therefore confine my discussion to the cylindrical rotor case.

On the basis of the assumptions stated in the paper, the vector diagram of Fig. 1 of the paper (p. 125 of ELECTRICAL ENGINEERING for January 1934) may be drawn for a cylindrical rotor machine. Within the accuracy of these assumptions the angle δ is the true phase position of the rotor of the actual saturated machine with respect to the system voltage e_e. The difficulty in analyzing the actual machine arises due to the occurrence of the saturation factor k in equations developed for the actual machine. The saturation factor k is a variable and must be treated as such in any calculations requiring differentiation.

In the paper under discussion this situation is simplified by replacing the actual machine by an "equivalent" unsaturated machine which may be considered to have a constant excitation e_{eq} and a constant reactance x_{eq} for differentially small changes away from any given operating point. The 2 machines have the same resistance, leakage reactance, and air gap voltage, and at any given operating point they are indistinguishable as far as terminal operating conditions are concerned. However, they are not alike if we cross the air gap and consider rotor phase positions; i. e., the rotor phase position angle δ_{eq} of the unsaturated machine with respect to the system voltage e_e is not the same as the angle δ of the actual machine, as is clearly shown in Fig. 1 of the paper. Hence the synchronizing power coefficient $dP/d\delta_{eq}$ of the unsaturated machine is not the same as the synchronizing power coefficient $dP/d\delta$ of the actual machine unless the difference between the angles, i. e., $\delta - \delta_{eq}$, remains constant for a differential change in load. Concerning this apparently important point the paper is silent. In the paper, in eq 14 and the sentence following it, it is apparently assumed that $dP/d\delta = dP/d\delta_{eq}$. If this is true, the burden of proof rests upon the authors of the paper under discussion. If it is not true, an approximation is introduced, the importance of which should be discussed.

That the synchronizing power coefficient $dP/d\delta_{eq}$ of the "equivalent" machine is not always equal to the synchronizing power coefficient of the actual machine may readily be seen by considering the following simple example. Consider a cylindrical rotor synchronous machine with negligible resistance directly connected to an infinite bus of constant voltage e_t and with constant excitation e_d. The power-angle equation for this machine is:

$$P = \frac{e_d e_t}{x_d - x_l + kx_l} \sin\delta \qquad (1)$$

This equation is exactly like eq 12 in the paper with $x_e = 0$ and therefore $e_e = e_t$. Differentiating with respect to δ, and remembering that k is a variable:

$$\frac{dP}{d\delta} = \frac{e_d e_t}{x_d - x_l + kx_l}\cos\delta - \frac{e_d e_t x_l}{[x_d - x_l + kx_l]^2}\sin\delta \frac{dk}{d\delta} \qquad (2)$$

This is the correct expression for the synchronizing power coefficient of the actual machine. The difficulty arises in evaluating the term $dk/d\delta$, as the paper points out. But suppose the machine were operating as a synchronous condenser. Then $\delta = 0$, $\cos\delta = 1$, and $\sin\delta = 0$, and the term involving $dk/d\delta$ drops out. Hence we obtain for the synchronzing power coefficient of an actual saturated synchronous condenser with constant field current and directly connected to an infinite bus:

$$\frac{dP}{d\delta} = \frac{e_d e_t}{x_d - x_l + kx_l} \qquad (3)$$

Consider the machine used as an example on p. 127 of the paper. Let us operate the machine as a synchronous condenser at rated kilovolt-amperes and normal terminal voltage. Then

$e_t = 1.00 \quad i = 1.00 \quad \phi = \theta = 90$ deg

$x_d = 1.11 \quad x_l = 0.11 \quad x_d - x_l = 1.00$

$e_l = e_t + ix_l = 1.11$

$e_d = 2.4$ (assumed)

$k = 1.27$ (from Fig. 6)

$e_d = ke_l + i(x_d - x_l) = 2.41$

$1 + a/b = 2.68$ (from Fig. 7)

$kx_l = 0.14 \quad x_d - x_l + kx_l = 1.14$

Therefore

$$\frac{dP}{d\delta} = \frac{2.41 \times 1.00}{1.14} = 2.11$$

This is the synchronizing power coefficient of the actual synchronous condenser to within the accuracy of our fundamental assumptions.

(I have used this same method to calculate the no-load synchronizing power of a 44-kva cylindrical rotor machine with the following constants and load conditions:

$e_t = 1.20 \quad i = 1.00 \quad \delta = 0$

$x_d = 0.97 \quad x_l = 0.11 \quad r = 0.02$ (neglected)

$k = 1.39 \quad a/b = 1.77$

For this machine the calculated value of synchronizing power is 4 per cent less than that obtained by measuring the slope of the experimentally determined power-angle characteristic. Hence, this calculation can be relied upon to within engineering accuracy.)

According to eq 14 of the paper:

$$\frac{dP}{d\delta_{eq}} = \frac{e_{eq} e_t}{x_{eq}} \cos\delta_{eq}$$

when $x_e = 0$. And according to eq 5 of the paper:

$$x_{eq} = x_l + \frac{x_d - x_l}{k\left[1 + \frac{a}{b}\right]}$$

for a synchronous condenser. Hence, for the machine used as an illustration in the paper:

$$x_{eq} = 0.11 + \frac{1.00}{1.27 \times 2.68} = 0.40$$

$$e_{eq} = e_t + ix_{eq} = 1.40$$

$$\delta_{eq} = 0, \cos\delta_{eq} = 1.00$$

Therefore

$$\frac{dP}{d\delta_{eq}} = \frac{1.40 \times 1.00}{0.40} = 3.50$$

But

$$\frac{dP}{d\delta} = 2.11, \text{ as previously shown.}$$

Hence, for this case, the discrepancy between the synchronizing power coefficient $dP/d\delta$ and the synchronizing power coefficient $dP/d\delta_{eq}$, as calculated by eqs 5 and 14 of the paper, is 66 per cent of $dP/d\delta$.

Results obtained by the application of the methods of the paper, as in eq 14 and Fig. 9 of the paper, give the synchronizing power coefficient $dP/d\delta_{eq}$ of the "equivalent" machine, which in itself does not appear to have any particular significance if it may differ so widely from the synchronizing power coefficient $dP/d\delta$ of the actual machine.

It may be argued that the above case is not one of practical importance, and perhaps it is a case in which the difference between $dP/d\delta$ and $dP/d\delta_{eq}$ is unusually large. However, if a discrepancy of this magnitude occurs for any case, it is sufficiently significant to warrant my request that the authors of the paper justify their apparent assumption that the results obtained for the synchronizing power of the "equivalent" machine are directly applicable to the actual machine.

R. H. Park: Messrs. Crary, Shildneck, and March have presented an interesting extension of synchronous machine theory which is directly applicable to the problem of steady state stability, and which should be of considerable practical utility. As an example of its usefulness it would appear that "equivalent reactance" would be preferable to short-circuit ratio as a means of specifying degree of inherent steady state stability. The usefulness of the paper in this or other ways, however, would be increased if a further analysis were presented in which certain of the assumptions employed were carefully examined, and the method of computing curves of the type shown in Fig. 5 of the paper explained.

While well suited to the purpose for which it was intended the method of analysis presented nevertheless suggests the desirability of a more general analysis which is not limited to steady state conditions and which does not require any assumption in regard to the effects of the system to which a machine may be connected.

Now it may be noted that actually saturation does not interfere with the linear relations obtaining between small changes in the flux linkages and currents in the various circuits of a machine, but may rather be regarded as merely modifying the constant coefficients which obtain when saturation is absent. Saturation will, however, introduce an element of assymetry under other than no-load conditions and consequently requires the introduction of coefficients which are absent or which may be thought of as having zero value when saturation is absent. Thus for a machine with no rotor circuits other than the field but with both direct and quadrature axis field windings the equations for armature and rotor flux linkages may be written in the form,

$$\psi_d = m_{fdad} i_{fd} + m_{fqad} i_{fq} + m_{adad} i_d + m_{aqad} i_q$$
$$\psi_q = m_{fdaq} i_{fd} + m_{fqaq} i_{fq} + m_{adaq} i_d + m_{aqaq} i_q$$
$$\psi_{fd} = m_{fdfd} i_{fd} + m_{fqfd} i_{fq} + m_{adfd} i_d + m_{aqfd} i_q$$
$$\psi_{fq} = m_{fdfq} i_{fd} + m_{fqfq} i_{fq} + m_{adfq} i_d + m_{aqfq} i_q$$

and imply the existence of per unit vector operators of the form,

$$x = \begin{pmatrix} x_d & x_{dq} \\ x_{qd} & x_q \end{pmatrix}$$

It would appear that in some cases the use of the assymetric equations given above, which are independent of the system to which the machine is connected, and which include transient as well as steady state conditions would possess advantages. Also, there is a use for this type of theory even when saturation is absent. Thus, although the capacitor motor, for example, may be analyzed by applying alternating current to the fields of a synchronous machine with the armature short circuited, the same thing cannot be done for a shaded pole motor unless the conception of an assymetrical magnetic structure is introduced.

In connection with the flux linkage equations given it may be helpful to note that if absolute direct and quadrature quantities be defined in accordance with the relations,

$$Q_d = \sqrt{\frac{2}{3}} \left\{ Q_a \cos\theta + Q_b \cos (\theta - 120°) + Q_c \cos (\theta + 120°) \right\}$$

$$Q_q = - \sqrt{\frac{2}{3}} \left\{ Q_a \sin\theta + Q_b \sin (\theta - 120°) + Q_c \sin (\theta + 120°) \right\}$$

rather than in the usual way all of the reciprocal mutal coefficients are equal, i. e., not only are $m_{aqad} = m_{adaq}$, $m_{fdfq} = m_{fqfd}$ and $x_{dq} = x_{qd}$, but also $m_{fdad} = m_{adfd}$, $m_{fqad} = m_{adfq}$, $m_{fdaq} = m_{aqfd}$, and $m_{fqaq} = m_{aqfq}$. The usefulness of this change in form, it may be added, is not restricted to cases in which assymetry is present.

In connection with the analysis of shaded pole or similar assymetric machines it should be noted that obliquity in the axes *fd* and *fq* does not require obliquity in the axes *d* and *q*. To avoid confusion however, replacement of the notation *fd* and *fq* by *f1* and *f2* would seem desirable. Evidently extension to a multiplicity of assymetric field windings is possible.

G. C. Dahl: This paper represents the first attempt at a rational analysis of the effect of saturation on the synchronous reactance of salient pole and nonsalient pole machines. The results are valuable and the methods presented give the equivalent saturated reactances to be used under specified conditions of load. Excepting the performance charts which correctly include the effect of saturation, previous schemes of selecting the proper saturated reactance have, as the authors point out, been largely empirical. Nevertheless it is believed that some of these may be sufficiently accurate and give calculated results to engineering accuracy.

In this connection I should like to call attention to an extremely simple *empirical method* which I have occasionally used for more than a dozen years with quite satisfactory results. The method is particularly applicable to nonsalient pole machines but also may serve as an approximation for salient pole machines. In either case it involves the representing of the machines by a single synchronous reactance and the use of a voltage (excitation voltage) behind this reactance selected from the open circuit magnetization curve at the field current at which the machine is operating.

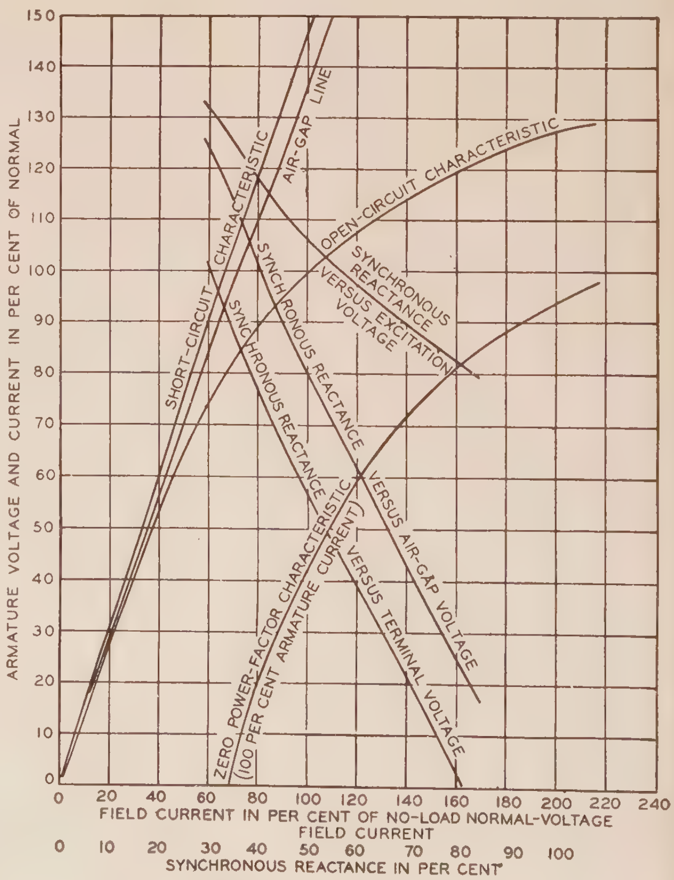


Fig. 1. Synchronous reactance vs air gap voltage

The air gap voltage under the particular operating conditions considered is used as the criterion of the degree of saturation in the machine. From an open circuit and a zero power factor curve synchronous reactance for various values of terminal voltage (and corresponding excitation voltage) may be determined and the air gap voltage for each of these values computed. A curve of synchronous reactance versus air gap voltage may then be plotted, as indicated in Fig. 1 of this discussion, which also shows the characteristics of the machine considered. Data for the synchronous-reactance curve are given in Table I of this discussion.

In solving a steady state synchronous machine problem by the use of the saturated synchronous reactance, the air gap voltage of the machine is first calculated for the desired operating condition by adding the leakage reactance drop vectorially to the terminal voltage. The curve of synchronous reactance versus air gap voltage (Fig. 1) is entered and the proper reactance selected. This then is used in the further solution of the problem using, as already mentioned, an excitation voltage directly obtained from the open circuit magnetization curve at the field current at which the machine operates.

The method disregards any effect of power factor in that the synchronous reactance is obtained under zero power factor conditions. This approximation, however, does not seem to be serious. The effect of current magnitude is more important. Fig. 2 of this discussion shows a family of synchronous-reactance curves for the same machine for various values of current. It will be noted that although there is some

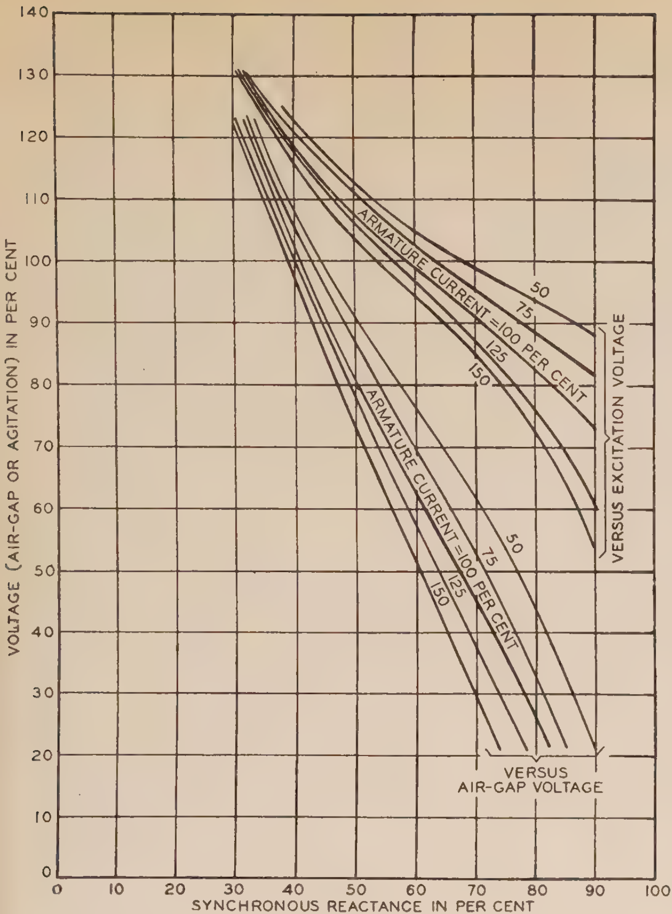


Fig. 2. A family of synchronous reactance curves

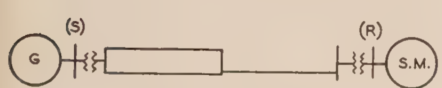


Fig. 3. Diagram of 2-machine system

difference in the values of synchronous reactance, its variation with current is not excessive. It is believed that in many problems, therefore, especially such where the general data otherwise may be uncertain, it is sufficiently accurate to use synchronous reactances obtained on the basis of 100 per cent current under all conditions.

The method, which admittedly is empirical, has been checked by a number of field current calculations for machines of various types. Over the whole range of loads as well as power factors the check between field currents so calculated and those obtained by more correct analysis (for instance, by the general method or by charts) has been very satisfactory. Certain test values have also agreed well with the calculated results.

The method has further been checked by applying it to the calculation of the power limits of 2-machine systems. Results from the system shown in Fig. 3 of this discussion, consisting of a synchronous generator supplying power to a synchronous motor over a transmission circuit involving a long line with step up and step down transformers, may be referred to as representative. Using synchronous reactances selected as above, and the general method presented by Edith Clarke in her paper "Steady-State Stability of Transmission Systems" (A.I.E.E. TRANS., v. 45, 1926, p. 22) the maximum power which could be transmitted to the motor under conditions of normal (100 per cent) bus voltages was obtained by a series of trial-and-error computations. The power of the machines had to be assumed initially in order that the synchronous reactances and the field currents and excitation voltages could be determined. A value of maximum power was calculated next, and it was checked whether this value was consistent with the initial assumption. If not, adjustments were made involving new and improved values of synchronous reactances and excitation voltages and the maximum power recalculated. In this manner a correct result was ultimately obtained.

The same system next was analyzed by graphical methods in which the machines as well as the transmission circuits were represented by appropriate performance charts. The machine charts included the effect of saturation. Assuming a value of load at normal bus voltages, a system characteristic in terms of power versus voltage at the motor terminals (stability curve) was obtained by proper manipulation and superposition of the various charts. Repeatedly using other "initial" power values, several such curves (as a rule 3 or 4 are sufficient) were determined. By extrapolation of the maxima of these separate power voltage characteristics the maximum power at normal bus voltages was obtained. The graphical solution gave essentially the same value as that calculated analytically by the synchronous-reactance method described.

Table I—Calculation of Data for Synchronous Reactance Curves
(Normal armature current at zero power factor lagging)
(All quantities in per cent)

Field Current	Excitation Voltage	Terminal Voltage	Leakage Reactance Drop	Air Gap Voltage	Synchronous Reactance
0	0	−70.2	23.2	−47.0	70.2
14.5	20.0	−61.3	23.2	−42.1	81.3
46.0	60.0	−31.8	23.2	− 9.6	91.8
68.5	81.2	0.0	23.2	23.2	81.2
100.0	100.0	41.6	23.2	64.8	58.4
123.0	108.8	61.6	23.2	84.8	47.2
140.5	114.2	72.0	23.2	95.2	42.2
161.0	119.9	81.2	23.2	104.4	38.7
193.0	126.4	92.0	23.2	115.2	34.4
228.0	130.8	100.0	23.2	123.2	30.8

DATA ON MACHINE

1. 37.5-kva (30 kw at 0.8 power factor), 240-volt, 3-phase (Y-connected), 60-cycle, 1,200-rpm, salient-pole alternator (G. E. Serial No. 305,977).
2. Short circuit ratio = 1.46
3. Armature resistance per phase = 0.053 ohm (3.44 per cent)
4. Armature leakage reactance (by Potier method) = 23.2 per cent
5. Ratio of pole arc to pole pitch = 0.67
6. Field current to give normal voltage on open circuit = 3.73 amp.

S. B. Crary, L. A. March, L. P. Shildneck: We consider the method of testing for equivalent reactance which Mr. Butler has presented in his discussion a valuable contribution to the technique of testing for equivalent reactance of salient-pole machines. It provides a simple method for testing for the relative values of equivalent reactance of different machines under conditions closely approximating their actual load conditions—full load field current and full load fundamental air gap density. Some correction is necessary, especially in the case of unity power factor machines, to allow for the difference in the direct axis flux, e_{ld}, and the total flux, e_l. However, even in the case of unity power factor machines the method suggested by Butler will indicate very well the relative steady-state stability characteristics of the machines. We agree with Mr. Butler that the A.I.E.E. should consider standardizing the definition of leakage reactance.

We agree with Mr. Dwight that, "a very satisfying test for the over-all accuracy for the method of calculation is to show maximum power in kilowatts, by test and by calculation." Unfortunately, the tests of pull-out power which we have available are not very satisfactory. The test data that we have were made under conditions such that the machines pulled out of synchronism with very little or no saturation, and no measurement was made of their power-angle displacements before they reached the pull-out angle. The data we have could all be checked very well neglecting saturation entirely or including only a slight correction for it. We expect to have available in the near future tests in which appreciable saturation exists at pull-out and thus check the method under the conditions suggested by Mr. Dwight. All of our checks with tests have been made by comparing test and calculated excitations and volt-ampere characteristics. These comparisons have been very satisfactory.

Mr. Dwight's results in determining the natural frequency of oscillation of a synchronous machine should prove interesting

However, unless the frequency of oscillation is very small, the transient reactance and circuit time constants will also play an important part in determining the natural frequency, so that an "adjusted" value of synchronous reactance cannot be used directly in its determination.

It should be emphasized that the equations Mr. E. H. Freighburghouse develops are for the particular case of constant power factor and should not be confused with the general equations for x_{eq}. However, there are numerous constant power factor cases such as condensers, marine synchronous motors, and generators, etc., so that these equations are very valuable. They are also very interesting from the test possibility standpoint. The condition of constant power factor can be very easily realized in test and x_{eq}, therefore, readily obtained under these conditions. Mr. Butler's discussion is an example of the use of a zero power factor volt-ampere characteristic to approximately determine the equivalent reactance of a salient pole machine.

Mr. Beckwith points out the importance of properly analyzing for the effect of saturation. Mr. Beckwith states, "the relative unimportance of transient stability will allow normal operation to be much closer to the steady-state stability limit than in most other comparable systems." This statement, we believe, will be applicable to more and more systems in the future. With the types of breakers and relays now available, the transient limitations are approaching more closely those of steady-state. This will make highly desirable in the future a more accurate determination of the steady-state limits.

We cannot agree with Mr. Beckwith that the saturation curve to be used in determining the equivalent reactance differs from the no load saturation curve only by an amount due to the change in field form with change in load, for two reasons. First, if appreciable saturation exists in both the stator and the rotor it is necessary to consider the fluxes in the rotor and stator separately because of the difference between, e_{ld}, the direct axis flux, and e_l the total air gap flux. Second, in the case of salient pole machines, the amount of saturation in the rotor depends considerably upon the field leakage flux. The total field flux may change as much as 30 or 40 per cent depending upon the load.

By neglecting these important factors, Mr. Beckwith obtains the relatively simple equation given in his discussion for the equivalent reactance. This equation is similar to equation (11) of the paper and is identical with that suggested by C. A. Nickle and referred to in reference 2 of the paper, except that Mr. Beckwith uses e_{ld} rather than e_l, on the no load saturation curve to obtain the ratio of the slope of the saturation curve to the slope of the air-gap line. Beckwith's Fig. 5 shows very clearly and ingeniously the wide range that x_{eq} may be expected to take with change in the operating condition. His Fig. 6 is further confirmation that x_q or $x_{q(eq)}$ has very little influence on the actual pull-out power. However, this should not be interpreted to indicate that the effect of quadrature axis flux in influencing the value of direct axis flux is unimportant. However, the error involved in making this latter approximation can be easily evaluated by means of equations (C-9) and (C-14) in the paper. The approximate equation which includes all factors (C-14), differs from the approximate equation which would be obtained if the effect of quadrature axis saturation on the direct axis flux were neglected (C-9), by a factor in the denominator equal to $k_1\frac{a_1}{2b_1}$. This factor depends only on stator saturation. Therefore, if the stator saturation is small compared with the rotor saturation, the effect of quadrature axis saturation on the direct axis flux can be neglected without appreciable error.

Mr. Evans compares the use of an empirical method which has been used in stability work with that given in the paper. This method, as most empirical methods, cannot be expected to give correct results over the whole range of operation or does not provide a satisfactory method of predicting the performance of machines whose designs depart from the conventional. Mr. Evans' method will tend to give too low values of equivalent reactance, especially if there is less than normal saturation existing in the machine at the operating point being considered. This is also borne out by the table given in Mr. Kilgore's discussion. Although Figs. 8 to 11 do not show the effect of change in field current on the equivalent reactance, Figs. 5, 6, 7, 10, and 11 can be used very readily to obtain values of equivalent reactance with field current as a variable.

We agree with Mr. Evans that the equivalent reactance will not supplant the use of short circuit ratio as an index for measuring the sizes of machines and transient reactance for determining their transient stability characteristics. It was not intended for such purposes. However, we do believe that projects similar to the one mentioned by Mr. Beckwith and systems similar to those now in operation which will not depend upon exciter performance to hold them in synchronism will continue to be built and that the equivalent reactance or some similar characteristic of the machine will be used to determine the increasingly more important steady-state stability limits.

Mr. Kilgore, as does Mr. Evans, apparently favors the use of empirical formulas for taking into account the effect of saturation. We believe that a rational method for the calculation of equivalent reactance when the necessary data is available leaves little justification for the use of empirical methods. The use of empirical methods, which do not show properly the effect of saturation, tends to retard improvement in design and understanding of the phenomena. The routine use of saturation factors in rational design methods would seem to justify their use in the calculation of equivalent reactance. Tests can be made to test the accuracy of such design factors and indirectly the values of equivalent reactance.

By assuming the stator saturation to be a function of the voltage back of leakage reactance, the effect of the harmonic fluxes produced by the quadrature axis mmf. is neglected. These parasite fluxes congest the iron paths of the fundamental fluxes and affect the final result only to the extent that they change the required fundamental mmf. By neglecting pole tip saturation no appreciable error is involved except in machines which have relatively heavy amortisseur windings in comparison with the size of the pole tip or have an unusual pole tip construction. Appreciable pole tip saturation is more likely to occur in small motors which usually operate against an infinite bus and have no saturation at pull out.

Table II of Mr. Kilgore's discussion shows the error to be of second order magnitude in determining the field excitations, even if the burden of the total discrepancy between tested and calculated results is placed on the aforementioned assumptions. As another example, when the method described in the paper is used, the ratio of the calculated to tested field current of the large slow speed waterwheel generator of Fig. 10 is 99.2 per cent at unity power factor, normal voltage, and kva. The first set of values in Mr. Kilgore's table for the calculated field currents can be obtained from design data before the machine is built, the second, third, and fourth sets of values are dependent upon values obtained from tests made on the actual machine. In this light, the accuracy with which the field currents were predicted is remarkably good. All methods which involve Potier reactance are of little value except for the calculation of excitation from test data, even then the method is empirical for other than zero power factors. Potier reactance varies over a wide range for salient-pole machines depending on the load saturation and may become two or three hundred per cent of the leakage reactance (Mr. Kilgore's shows a ratio of 225 per cent). Any attempt to calculate Potier reactance must involve the calculation of saturation coefficients, the major objection voiced by Mr. Kilgore. We believe that a method involving reactances, which are independent of saturation, and saturation coefficients which are dependent on the load and power factor has much to recommend it over the present widely used methods of calculating excitation and equivalent reactance.

The question of the relation between the actual and the equivalent synchronizing power coefficients which Mr. Kingsley's discussion raises applies only to the cylindrical rotor case, as the salient pole machine has the same load angle, δ, as the actual machine and the equivalent reactances, $x_{d(eq)}$ and $x_{q(eq)}$, were determined so that the equivalent machine would have the same de_{ld}/di_d, de_{lq}/di_d, di_q/di_d and $d\delta/di_d$ as the actual machines.

Equation (14) of the paper has a typographical error. It should read

$$\frac{dP}{d\delta_{(eq)}} = \frac{e_{eq}e_e}{x_{eq} + x_e} \cos \delta_{eq} \qquad (14)$$

as it was obtained directly from equation (13). The statements following the equation in the paper could be revised to more accurately state, "therefore, the synchronizing power coefficient of an equivalent machine which indicates the stability of the actual machine can easily be written in terms of the equivalent reactance, excitation and angle." That is, $dP/d\delta_{eq}$ does not necessarily equal $dP/d\delta$. However, $dP/d\delta_{eq}$ indicates the stability of the actual machine. This is illustrated by Fig. 4 of this discussion, which presents a comparison between the actual and the equivalent

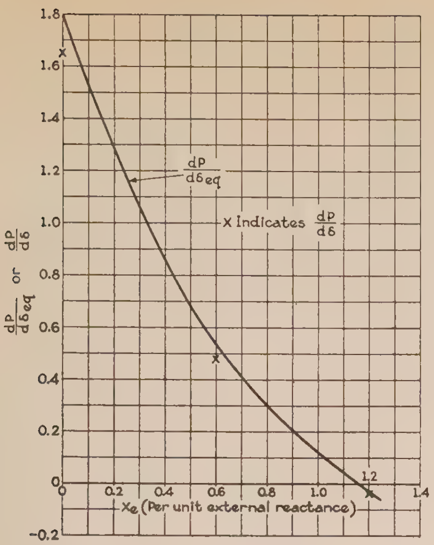


Fig. 4. Actual and equivalent synchronizing power coefficients of a cyclindrical rotor synchronous generator connected to a system through external reactance, normal voltage, normal kilovoltamperes, 0.8 power factor lagging

synchronizing power coefficient for the case of $r_e/x_e = 0$ of Fig. 9 of the paper. It should be noted that $dP/d\delta$ and $dP/d\delta_{eq}$ equals zero for the same value of external reactance. This would be expected since the equivalent machine has the same response as the actual machine for any changes as its terminals, and the angle between e_d and e_l of the actual machine and between $e_{d(eq)}$ and el can be expected to increase with increase in δ_{eq} and δ for the usual ratios of external resistance to reactance. Some error may be involved for unusual conditions but this is not expected to be appreciable at pull out. In any case the actual synchronizing power coefficients can be calculated, if necessary.

The derivation for the formula used in Fig. 4 of this discussion for the actual synchronizing power coefficient in the case of zero external resistance follows

From equation (12)

$$P = \frac{e_d e_e}{x_d - x_l + k(x_l + x_e)} \sin\delta$$

Differentiating,

$$\frac{dP}{d\delta} = \frac{e_d e_e}{x_d - x_l + k(x_l + x_e)} \cos\delta - \frac{e_d e_e (x_l + x_e)}{[x_d - x_l + k(x_l + x_e)]^2} \sin\delta \, \frac{ak}{be_l}\frac{de_l}{d\delta} \qquad (1)$$

The only unknown is $de_l/d\delta$. This can be obtained from the following relation.

$$e_l^2 = \left[e_e + \left(\frac{e_d}{k}\cos\delta - e_e\right)\frac{k(x_l + x_e)}{x_d - x_l + k(x_l + x_e)}\right]^2 + \left[\frac{e_d}{k}\sin\delta\,\frac{k\,(x_l + x_e)}{x_d - x_l + k(x_l + x_e)}\right]^2 \qquad (2)$$

Differentiating and simplifying,

$$\frac{de_l}{d\delta} = \frac{\dfrac{e_d\,(x_l + x_e)}{x_d - x_l + k(x_l + x_e)}[\sin\alpha\cos\delta - \cos\alpha\sin\delta]}{1 + \dfrac{(x_l + x_e)e_e\cos\alpha}{[x_d - x_l + k(x_l + x_e)]}\dfrac{ak}{be_l} + \dfrac{(x_l + x_e)^2}{x_d - x_l + k(x_l + x_e)]^2}\dfrac{ak}{be_l}[e_d(\cos\alpha\cos\delta + \sin\alpha\sin\delta) - k_e\cos\alpha]} \qquad (3)$$

where α is the angle between e_e and e_l.

The numerical comparison that Mr. Kingsley has made between the synchronizing power coefficient of the actual and the equivalent machine is incorrect as he used equation (5) to determine the equivalent reactance. Equation (5), as stated in the paper, is based on the restrictions that $\phi = 90°$ and $d\phi = 0°$. These are the conditions for the operation of a synchronous condenser, but they are not the conditions for the operation of a machine whose load angle changes with respect to its terminal voltage. That is, for Kingsley's case $\phi = 90°$ but $d\phi$ must be determined. This can be done by solving equation (3) and (B-4) simultaneously to determine de_l/di and $\cos\phi\,\dfrac{d\phi}{di}$ for the conditions of the problem. It is interesting to note that for this case, although $\phi = 90°$ and $\cos\phi = 0$, $\cos\phi\,\dfrac{d\phi}{di}$ has a definite value and is not necessarily equal to zero. Solving correctly for the equivalent synchronizing power coefficient a value of 2.45 is obtained instead of 3.50, the value obtained by Kingsley. The actual synchronizing power coefficient is 2.11.

We quite agree with Mr. Park that a more general method of analysis would be desirable and believe that such a method will be forthcoming in the near future. Although the equations for equivalent reactance that we have developed depend upon the connected system, equation (3) for the cylindrical rotor machine, equation (C-2) for the direct axis of the salient-pole machine and a similar equation for the quadrature axis which can be obtained from equation (B-2) are not. These equations can be solved directly for any set of conditions at the terminals involving small changes. However, these equations, as Mr. Park points out, are limited in their application because they neglect the effect of additional circuits and were derived for steady-state conditions only.

Simultaneous Control of Voltage and Power Factor

Discussion of a paper by L. F. Blume and F. L. Woods published in the December 1933 issue, p. 884–9, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 483.

R. N. Slinger: Messrs. Blume and Woods have called our attention to a scheme by which 2 well-known devices may be combined and made to operate as a single unit. The consideration of a practical application brings up several interesting questions, one of the first being: What are the operating advantages of such a device?

The authors have mentioned some of the advantages but there are a number they have omitted. The merits of the step voltage regulator alone are already known as are also the merits of capacitors used for power factor correction. The important point is that there appears to be no basic reason why all of the respective operating advantages of each of these 2 devices should not be retained when they are combined, as the authors have suggested.

In addition, there are further advantages of an economic nature that accrue from such a combination of regulating transformer and capacitor. The former seems inherently well suited to serve as an automatic control device for the capacitor, at the same time that it is performing its normal function as a voltage regulating device. Thus, more efficient operation of the regulated circuit than could be obtained with the insertion of a fixed block of corrective kilovoltamperes is possible without incurring any extra expense for oil circuit breakers or other control equipment. Furthermore, because such a regulator would be inherently automatic in operation it could be located at a point on a system where the services of an operator are not available.

It may also be pointed out that the variable corrective kilovoltamperes provided by this new regulator would reduce the wattless requirements of the regulated circuit and would result in improved voltage conditions for all loads tapped off at intermediate points.

The next question is: What is the proper application for such a device? It is essentially a new and improved form of step voltage regulator. Hence, it is only logical to conclude that wherever an ordinary step voltage regulator could be applied to advantage, there is a possibility that operating economies and improved operation may be obtained with this new scheme.

In the low capacity field, the step voltage regulator usually can be shown to have definite economic advantages over its chief competitor, the induction regulator, for all voltages above 4,800 volts. In some instances, depending upon local conditions, the step regulator also has the advantage in the moderate capacity range over synchronous condensers, whose cost per kilovoltampere is relatively high in the small ratings. Therefore, it seems only reasonable to expect that the most favorable field of application for the new type of regulator probably will be on small and medium capacity stub feeders where the load power factor is low and the line voltage is above 4,000 volts.

Another question of interest is: How much corrective kilovoltamperes should be included in the form of capacitors with this new regulator? Theoretically there should be no limit to the amount that could be added, although there are certain practical limitations. In all cases a point would finally be reached beyond which it would be less expensive to obtain the required amount of corrective kilovoltamperes by means of synchronous condensers. In addition there would also be practical limitations imposed by the current carrying capacity of the ratio adjusters and the various windings of the regulating transformer.

The amount of capacitor kilovoltamperes that ought to be included is strictly an economic problem with a right amount for each individual case which is dependent upon such things as magnitude of the peak load, load factor, power factor, cost of energy, etc. In arriving at this economic balance the cost of capacitors in various ratings should be balanced against the capitalized value of the corresponding improvement in power factor conditions. Later on as the load builds up it may be economically advantageous to add additional capacitor kilovoltamperes to compensate for load growth. By following such a program, an appreciable part of the investment which is represented by the capacitors may be deferred until such time as there is economic justification for it.

E. K. Shelton: In the novel method proposed by the authors for control of voltage and power factor on transmission systems, a combination of 2 types of electrical apparatus is used—the load ratio control transformer and the capacitors. The first is a quite familiar type of equipment to transmission engineers, and well established in service. The use of capacitors in this field, however, represents a novel application. To many transmission engineers, the question of reliability and service performance of the capacitors will present itself. I desire to emphasize briefly the present status of capacitor development which has placed this useful and widely applicable tool on a plane of service performance fully equal to that of the more commonly used and better known forms of electrical apparatus.

The first real impetus was given to this development when the problem of low power factor became of major importance in the power distribution field. This brought the capacitor actively into the industrial field and from then on, the advance in this development has been steadily accelerated. Within the last 3 years, the waxes and mineral oils have been replaced, to a large extent, by an entirely new synthetic treating material of vastly improved stability, both from an electrical and chemical standpoint. To this new class of liquid insulations, has been applied the name "pyranol" in recognition of the noninflammability of the material, and the nonexplosive nature of the vapors or products of decomposition when mixed with air. The high dielectric strength combined with a relatively high dielectric constant are obviously favorable factors in improving the economy of capacitor design.

High working stresses are a necessity from an economic standpoint, but these have been attained with a high factor of safety to breakdown voltage through the careful control of materials, more efficient treating processes and improved designs. Stresses of 400 volts alternating current (rms) per mil of dielectric, have been used for several years in capacitors for industrial application. Stability of electrical and chemical characteristics have been proved by the decrease in power factor with service on voltage and by the absence of any indications of chemical deterioration. The impulse strength of the dielectric is high, while the losses will not exceed 1/3 of one per cent.

The service record of many thousand kilovoltamperes of capacitors in industrial applications up to 6,600 volts over a considerable period of years, including several series capacitors in transmission line service, gives clear and conclusive evidence that the capacitor offers definite reliability for the proposed application. It is to be hoped that the theory may be proved by actual service trial in the near future.

Protecting Machines From Line Surges

Discussion of a paper by J. F. Calvert published in the January 1934 issue, p. 139–46, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions on this paper were published in the March 1934 issue, p. 488.

J. F. Calvert: First, I wish to thank Messrs. Beck and Montieth for their helpful discussions.

Along the lines of their discussions, it seems desirable to consider the protective scheme outlined in Fig. 16 of the paper. It will be assumed that the inductance and capacitance each can be treated as lumped constants. (The error in assuming the inductance as a lumped value is minimized by the use of relatively large capacitances.) It can be demonstrated mathematically that the surge impedance of the machine may be assumed infinite without appreciable effect on the results within the normal range of values encountered. It will be assumed that the voltage at the line end of the inductance is suddenly raised and maintained at a constant value.

Then let

E_{LL} = line to line voltage of the machine
Kva = full load machine rating
η = (full load current) reactance voltage of the inductance coil expressed as a decimal fraction of E_{LL}
f = normal machine frequency
L and C are the constants shown in figure 16 in henries and farads, respectively
e_2 = transient voltage across the condenser and machine due to the surge
t = time in seconds

Then,

$$e_2 = E_a\left(1 - \cos\frac{t}{\sqrt{LC}}\right) \tag{1}$$

$$L = \frac{\eta(E_L)^2}{2\pi f \times 1.73\ (\text{Kva}) \times 10^3} \tag{2}$$

$$\frac{de_2}{dt}\Big/\text{max.} = \frac{E_a}{\sqrt{LC}} = G_m \tag{3}$$

$$C = \frac{1}{LG_m^2} = \frac{t_a^2}{L} \tag{4}$$

where t_a = time in seconds for the voltage e_2 to rise to crest at the constant rate G_m.

From equation (25) of the paper and with a suitable factor of safety for the turn insulation, t_a can be computed. Then from equations (2) and (4) of this discussion, L and C can be determined for the protection of the turn insulation.

Effects of Rectifiers on System Wave Shape

Discussion of a paper by P. W. Blye and H. E. Kent published in the January 1934 issue, p. 54–63, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 483–4.

R. D. Evans and E. L. Harder: Messrs. Blye and Kent have made important contributions to the theory concerning the determination of harmonics in the supply circuits of rectifiers. Heretofore the methods which have been published have been based upon conventional rectifier theory assuming a supply circuit represented by an inductance whose reactance varies linearly with frequency. By means of the empirical formulas given in the first part of the paper, the authors have been able to take into account the effects of the actual impedances of supply circuits, particularly the amplification or reductions due to resonance or antiresonance of the supply system at a particular frequency. This is an important contribution.

In examining our 6-phase rectifier data good checks are obtained with the empirical formulas. However, we wish to offer the following:

$$I_n = \frac{V_{\phi-N}}{3n\sqrt{R_0^2 + Z_{c\,n}^2}}$$

for the 6-phase rectifiers and

$$I_n = \frac{K(V_{\phi-N})}{3n\sqrt{R_0^2 + \frac{(Z_{cn})^2}{2}}}$$

for the 12-phase rectifiers using the notation of the paper except that $Z_{cn} = Z_{tcn} + Z_{sn}$ (vectorially). The term Z_{tcn} is the commutating reactance of the rectifier transformer at harmonic frequency, and may or may not coincide with the nameplate reactance Z_{tn} used in the paper.

This modification of the empirical formula, eq 8 of the paper, is indicated by rectifie theory, and it is proposed to discuss the basis for it at a later date. The formulas just given are believed to give better results for high reactance supply circuits.

The authors have listed a number of remedial measures as follows:

1. Advance planning of method of supplying rectifier from the standpoint of minimizing wave-shape distortion.
2. Frequency selective devices.
3. Coördinated power circuit transpositions.
4. Reduction of power circuit unbalances, such as those caused by single-phase branches.
5. Coördinated telephone circuit transpositions.
6. Reduction of telephone circuit unbalances, such as those caused by the connection of ringer windings from one side of line to ground for selective ringing.
7. Shielding of telephone cable circuits by grounding the cable sheath.

Of these but 2 have been discussed in de-

tail, namely, system planning and frequency selective devices. The fact that detail discussion has been limited to these 2 items, tends to give them undue prominence. It seems pertinent, therefore, to point out that these are not necessarily the most effective methods of coördination. Advance planning and frequency selective devices are applicable to communication systems as well as to power supply systems. Also, in any particular case it may happen that the "best engineering solution" may not involve either of the 2 items discussed in detail in the paper. It is suggested that not only should these 2 methods receive attention in a particular case but that care should be taken not to overlook the other possibilities. All methods should be considered; whether applicable to the power supply system, the communication system, or the coupling between the systems. The choice of the measures to be used should, of course, be such as to provide the "best engineering solution," which has been stated in the "Principles and Practices" of the National Electric Light Association and Bell System.

P. W. Blye and H. E. Kent: Dr. Smith has asked as to the accuracy of the empirical formulas when estimated values of system impedance are used. As pointed out in the text the results given in Figs. 3 and 4 of the paper are based on cases in which measurements of the system impedance were available. Our experience indicates, however, that when estimated system impedances are used, while the calculated values of the individual harmonic currents may be somewhat less reliable, the over-all result as indicated by the product of the rms. current and its telephone interference factor (I.T.) is not appreciably affected. The accuracy of calculated individual harmonic voltages is a direct function of the accuracy with which the system impedance is known. However, in this case also errors in the individual harmonic voltages partially cancel one another and the reliability of the calculated voltage T.I.F. to which they contribute is much greater than that of the individual harmonic components. As an example of the accuracy attainable with the empirical formulas in cases in which the system impedance must be estimated, we should like to quote from a case which recently has been investigated. In this instance in which the system impedance was a very complicated function of frequency the estimated voltage T.I.F. was about 125. The measured T.I.F. was subsequently found to be 111, the error in the estimate being only slightly over 10 per cent.

In reply to the question regarding Fig. 3 of the paper the lower values in this figure include both light load conditions on large rectifiers and full load conditions on small rectifiers. In general, the empirical method has been found to work equally well for both cases.

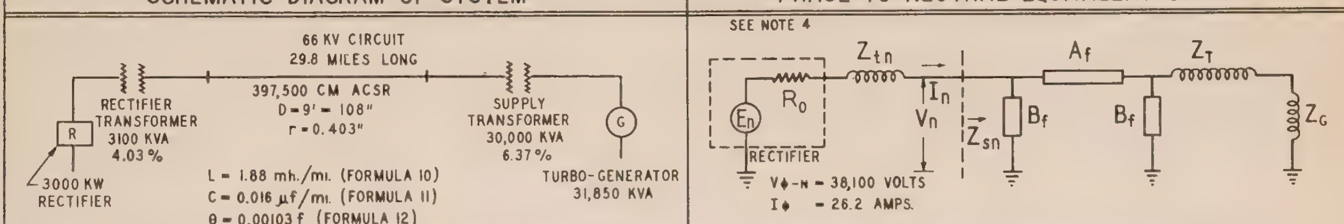
As suggested, a diagram (Fig. 1) has been prepared and is presented herewith indicating: (1) A single line diagram of a power system supplying a rectifier, (2) its equivalent circuit set up in accordance with the methods outlined in the paper, and (3) a table showing the magnitudes of the various impedances involved in the equivalent circuit over a range of frequencies as computed by the formulas given in the paper.

The authors agree with the point made by Dr. Smith to the effect that a large power system may not necessarily be a low impedance power system. In general, a large system does offer a low impedance to harmonic currents but in cases in which the impedance of a portion of the system is increased by the use of current limiting reactors, this relation no longer holds.

The authors are much interested in the modifications of the empirical formulas suggested by Messrs. Evans and Harder. We have not been able to check them against our tests results, however, as we have not had available the commutating reactances of the transformers involved. The fact that these reactances are not

SCHEMATIC DIAGRAM OF SYSTEM

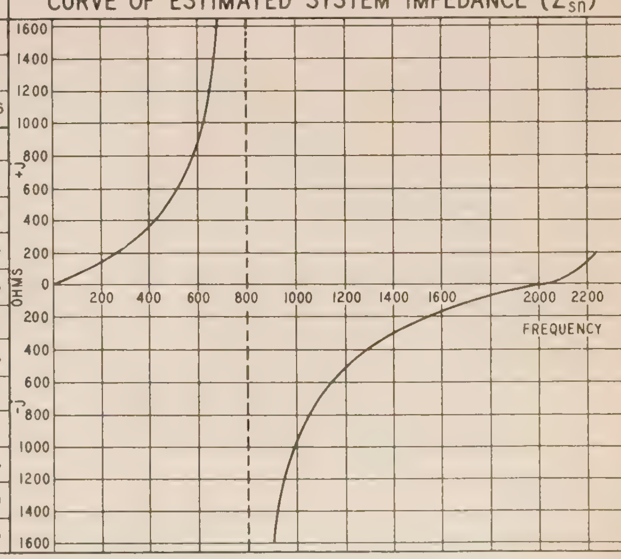
PHASE-TO-NEUTRAL EQUIVALENT CIRCUIT



CALCULATED VALUES FOR EQUIVALENT CIRCUIT

QUANTITY		E_n	R_0	Z_{tn}	A_f	B_f	Z_T	Z_G	Z_{sn}	Z_n	I_n	V_n
FORMULA		(4)	(3)	(18)	(13)	(14)	(18)	(34)	NOTE 1	NOTE 2	(6)	(7)
FREQUENCY	n	VOLTS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	AMPS.	VOLTS
300	5	2540	485	+j 283	+j 103	−j 2210	+j 46	+j 75	+j 258	+j 541	3.51	905
420	7	1815	485	+j 397	+j 144	−j 1540	+j 65	+j 105	+j 428	+j 825	1.9	813
660	11	1152	485	+j 623	+j 216	−j 970	+j 102	+j 165	+j 1475	+j 2098	0.54	796
780	13	977	485	+j 737	+j 245	−j 810	+j 120	+j 195	+j 12350	+j 13090	0.075	940
1020	17	747	485	+j 963	+j 298	−j 590	+j 157	+j 255	−j 913	+j 50	1.53	1400
1140	19	668	485	+j 1076	+j 313	−j 517	+j 176	+j 285	−j 584	+j 492	0.97	567
1380	23	552	485	+j 1300	+j 340	−j 400	+j 213	+j 345	−j 292	+j 1008	0.49	144
1500	25	508	485	+j 1415	+j 343	−j 353	+j 231	+j 375	−j 207	+j 1208	0.39	81
1740	29	437	485	+j 1640	+j 337	−j 274	+j 268	+j 435	−j 79	+j 1561	0.27	21
1860	31	409	485	+j 1755	+j 314	−j 241	+j 287	+j 465	−j 34	+j 1721	0.23	8
2100	35	362	485	+j 1980	+j 281	−j 185	+j 324	+j 525	+j 60	+j 2040	0.17	10
2220	37	343	485	+j 2100	+j 258	−j 151	+j 342	+j 555	+j 153	+j 2250	0.15	23

CURVE OF ESTIMATED SYSTEM IMPEDANCE (Z_{sn})



NOTE 1. Z_{sn} CALCULATED AS INDICATED IN PHASE-TO-NEUTRAL EQUIVALENT CIRCUIT

NOTE 2. $Z_n = Z_{sn} + Z_{tn}$

NOTE 3. ESTIMATE INDICATES THAT Z_{sn} IS NEARLY IN PARALLEL RESONANCE AT 780 CYCLES, AND IT IS NOT POSSIBLE TO DETERMINE THE VALUE OF Z_{sn} ACCURATELY. HOWEVER, THIS IS NOT NECESSARY, SINCE FOR ALL LARGE VALUES OF Z_{sn}, V_n APPROACHES THE THEORETICAL VOLTAGE E_n. FOR EXAMPLE, FOR VALUES OF Z_{sn} BETWEEN 2000 OHMS RESISTANCE AND INFINITY, V_n CHANGES ONLY FROM $0.8 E_n$ TO E_n. ESTIMATE ALSO INDICATES AN APPROACH TO SERIES RESONANCE BETWEEN Z_{sn} AND Z_{tn} NEAR 1020-CYCLES. IN THIS CASE ALSO, AN EXACT KNOWLEDGE OF THE SERIES RESISTANCE IS NOT REQUIRED SINCE FOR ALL SMALL VALUES OF Z_n, THE CURRENT I_n TENDS TO APPROACH A CONSTANT VALUE E_n/R_0. IF ACTUAL VALUE OF Z_n WERE 200 OHMS RESISTANCE, I_n WOULD BE 1.09 AMPERES AND V_n WOULD BE 995 VOLTS.

NOTE 4. ALL IMPEDANCES, VOLTAGES AND CURRENTS ARE REFERRED TO 66 KV

Fig. 1. An example of the calculation of system impedance and wave shape of supply to rectifier

generally available in the field would appear to make these modified formulas of more value to the manufacturers than to the field people who usually have at hand only the name-plate data on the various system equipment.

Messrs. Evans and Harder have commented on the fact that of the remedial measures listed in the paper only two have been discussed in detail. Due to the space requirements of the paper it was not practicable to discuss all the remedial measures available. Since data on the remaining measures listed had already been published, the detailed discussion was confined to the items on advance planning and frequency selective devices, subjects which had not been covered in previously published material. The authors agree that there is no single method of coördination to be applied universally, but that the most practicable solution in a given case can be arrived at only by a study of all the coördinative measures available. This conclusion has been brought out in the paper (item 5, page 55, of "Summary of Conclusions" and under "Coördinative Measures," pages 60 and 61).

and the extent of damage exceeded that expected, based on the cases which had previously come to the engineers' attention.

Both the power and telephone engineers on the Joint Subcommittee several years ago took steps to secure information on any contact which occurred between higher voltage distribution circuits and telephone circuits so that such cases could be promptly investigated and all of the pertinent facts obtained. As a result of this a large amount of data has already been secured and a number of investigations have been made. These include contacts involving not only joint use but also crossings and conflicts of the two classes of facilities. The data secured in these investigations have furnished a large amount of the basic material upon which the relative hazard studies have been carried forward.

Provisional Report No. 6 of the Joint Subcommittee on Development and Research referred to in the paper and also the paper on Joint Use presented before the A.I.E.E. by Messrs. Huber and Martin in February 1931, discuss the various factors which enter into the problem of relative safety and point out the necessity for obtaining coördination of protection of power and communication facilities in order to provide satisfactory over-all situations. Possible improvement in the telephone fuse referred to by Mr. Chase has been investigated, but an over-all appraisal does not appear to show that satisfactory protection could be obtained by relying solely upon an improved fuse.

It would be expected that a system engineered and operated with the high service standards employed in Philadelphia would naturally have a minimum number of contacts per year on the average. Furthermore, the method of grounding and the excellent relaying of the system would tend to minimize the effect of any contact which did occur. Experience has shown that the power companies are seldom, if ever, advised of contacts by the communication engineers unless material damage results.

The authors are of the opinion that the relative safety of joint use involving the higher voltage distribution is largely affected by the circumstances of the systems, such as the character of construction and the nature of the protective and other electrical features. It was a coördination study of these factors which brought a satisfactory solution in Staten Island.

Joint Use of Poles With 6,900-Volt Lines

Discussion of a paper by W. R. Bullard and D. H. Keyes published in the December 1933 issue, p. 890–8, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 489–95.

D. H. Keyes: P. H. Chase's discussion of the paper brings up several interesting and important factors which require consideration in any study of joint use of poles between power and telephone companies.

The foreign systems coördination committee of the former Natl. Elec. Light Assn. made an extensive, although not complete, survey in December 1932 which indicated approximately 1,400 miles of joint use in the United States between communication plant and higher voltage distribution circuits. Of this approximately 53 per cent was with the Bell System companies, 37 per cent was with the independent telephone companies, and 10 per cent could not be identified from the answers given. In general these represent specific situations where joint use was considered to be the most satisfactory over-all solution in particular situations usually involving a limited number of poles.

While this represents a considerable amount of construction, few systematic records of over-all performance were previously kept. Experience in one area where high voltage joint use has existed for a number of years indicates that in the absence of such records it is unjustifiable to conclude that such joint use is entirely satisfactory. In this particular instance, for example, after a systematic routine for investigating contacts between power wires and telephone plant had been established it was found that the frequency of contact

An Economic Study of Suburban Distribution

A. H. Sweetnam and C. A. Corney, January 1934 issue, p. 97–102.

Radial Versus Primary Network Distribution

H. E. Wulfing, January 1934 issue, p. 38–42.

Fundamentals of Design of Electric Energy Delivery Systems

J. Allen Johnson and R. T. Henry, December 1933 issue, p. 831–8.

Discussion of a group of papers presented for oral discussion at the session on power distribution of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of these papers were published in the March 1934 issue, p. 489–95.

R. E. Hellmund: After a great many years, during which the Institute records have shown a preponderance of interest in transmission problems, the present meeting and also some of the preceding ones have given the problems in distribution the attention they well deserve. However, the papers presented have dealt essentially with the broad problems in distribution having reference to the relative merits of radial and various kinds of network systems, location of substations, etc. The purpose of my discussion is to invite increased attention to the somewhat neglected ends of the distribution system, such, for example, as the leads and wiring to and on the customers' premises and the smaller distribution transformers. Technically, the problems connected with these items perhaps are or at least appear to be the simplest, and possibly this is the very reason why they have received the least attention. In addition, they may have been neglected because the layout and responsibility for them is divided among the utilities, the electric contractors, and the users.

The reason why increased attention to these ends of the distribution system is desirable is that more and also larger capacity motors are continuously being installed for motor-driven appliances, domestic and commercial refrigeration, air conditioning, etc., in districts which previously had rather light and uniform loads. The present practice is in general to install any type of commercial distribution transformer in more or less arbitrarily chosen locations, to install wiring meeting the underwriters' requirements, and motors of various standard types, and then to expect everything to work satisfactorily. If such is not the case, the stand is frequently taken that the connected equipment is at fault and possibly should be taken off the line.

Following are a few illustrations of this: With a relatively small compressor outfit, flickering of the lights was noticed when the equipment was running. An analysis indicated that with the particular ratio of the pulleys of the belt drive, the piston impulses caused load variations of a frequency of about 15 to 20 cycles a second, which with the line drops existing caused the lights to flicker. In another case trouble was experienced from a commercial refrigerating equipment due to low voltage during starting; in fact, the voltage drop was so large that the starting voltage was away below

established standards, and as a consequence improper functioning of the control resulted in a great deal of trouble and expense.

It is true that in each of these cases the connected equipment could have been changed to remedy the trouble. In the first case, a change from a low-power-factor, repulsion-start, induction-run motor belted to the compressor to an equipment with direct-connected capacitor motor would have corrected the trouble, or possibly a compressor with a larger number of pistons could have been used. The larger number of pistons and the direct-connected motor would have resulted in the frequency of the impulses being so high as not to be noticeable, and the higher power-factor of the capacitor motor would have reduced the variations of the line drop. In the second case, just the opposite change, that is, from the capacitor motor used in this case to a repulsion-start, induction-run motor, would have reduced the starting current and consequently the line drop during starting.

It should be realized, however, that insistence upon such changes and possibly upon additional and more exacting regulations with regard to the characteristics of the connected equipment, would not exactly prove beneficial to load building, especially since in either of the 2 cases a better planning of the wiring installation would have led to satisfactory results at a much lower expense. In the case where the voltage drop during starting was too high, it was found that the network to which the motors were connected had excellent voltage regulation and that somewhat heavier leads from the network to the motors would have taken care of the situation at an almost negligible increase in cost.

Although it may be impracticable for the utilities to engineer each individual motor installation, these problems should nevertheless be given increased attention. In many cases the use of low-impedance transformers may help out greatly in such situations. Again, it may be advisable in some cases to use larger distribution transformers serving a somewhat greater area, as a result of which any connected motor will represent a smaller percentage of the transformer capacity and thus cause lower voltage drops during starting or during variations in loads. Leads from such larger transformers serving larger areas will, of course, be longer and therefore may have to be made somewhat heavier, but the total cost of the installations may not be increased as one large transformer is usually cheaper than several small ones. At any rate, these or similar solutions may be more economical than any insistence upon features which unnecessarily increase the cost of the connected equipment, a practice which in many cases may retard the installation of additional load-consuming equipment.

E. W. Oesterreich: In analyzing the papers presented in the symposium on "power distribution" it was found that it was practically impossible to reconcile the apparent discrepancies in the basic conclusions, due to the absence of supporting cost data, or to the different basis of cost determination.

We can readily understand why topographical conditions may have a great influence on the relative unit capacity costs of the various distributing systems between the substation and the point of customer utilization. However, in this morning's presentation, the outstanding difference appeared to be that for the cost per kilovoltampere of firm capacity for distribution substations. Take for example the substation cost estimates when compared to the equivalent network unit estimates as presented by Messrs. Johnson and Henry, and Messrs. Sweetman and Corney. The Johnson and Henry paper shows the network unit installations as being approximately 75 per cent higher in capital investment cost than the equivalent substation installations. Messrs. Sweetnam and Corney indicate the opposite of this condition in that their network unit installation costs are approximately 42 per cent below the corresponding substation investment requirements. In another study recently completed by a company, which study involved an area of 11 square miles and a 1931 peak load demand of 32,000 kva, the analysis showed that for a distribution substation which incorporates the most recently proposed practices in economical substation design, the estimated investment cost could be lowered to a point where the total investment for the substation capacity would be approximately equal to the investment required for the network unit installations.

This wide spread in substation investment cost data would indicate not only a decided difference of opinion as to operating and engineering design requirements for a presupposed similar service requirement, but a large differential in the installation costs of the equipment.

Mr. Wulfing shows in his paper in "Table IX—Comparative Load-Capacity Table" that in the network plan the transformer units are installed as the load growth within the area under consideration and in the surrounding station area, requires the additional capacity while existing substation capacity is utilized to its fullest extent for the maximum period of time. In the radial feeder plan, the initial installation of the new substation appears to immediately release to the surrounding area, substation capacity of 4,000 kva in excess of that released, or rather unloaded, in the network plan. According to the table this additional released capacity amounts to a total of 14,500 kva in the first 6 years considered, or roughly, an average capacity of 2,500 kva for 6 years. To make the annual cost comparison applicable, it would appear that the annual cost of the equipment released, which is not used or useful in supplying capacity for the growth in load in the surrounding area, should be charged to the plan creating the idle investment condition. Or if all of the surrounding station capacity made available by the radial plan is necessary to supply immediate load requirements of the surrounding area, then it would seem more equitable if the cost of the difference in the amounts of this capacity used under the 2 plans should be charged to the network plan.

Messrs. Johnson and Henry present a worth while contribution to the industry by clarifying the fundamentals involved in the problem of economic design of distribution systems. Unfortunately, their presentation of comparative capital costs as shown in Table II is of such a general nature that the lack of data relative to items of the subdivisions prohibits comparisons with conditions as they exist on other properties.

A system composed of small increments of capacity, installed at or near the concentrated loads when needed, and feeding into a distribution system which does not require frequent, costly circuit revision work to adequately serve the increasing demands brought about by normal growth of load and the addition of new circuits, presents economic advantages which are apparent. But local conditions, construction practices, operating and service standards may impose such restrictions that the ideal condition cannot be obtained. The papers presented force us to recognize the engineering, economic, and operating phases of distribution as a problem which cannot be effectively subdivided into component parts such as transmission, substation, and distribution. For each of the related phases and for the composite system there is a solution which results in the lowest annual costs over a reasonable period of time. It is this solution which we must strive for regardless of precedence, and existing functional jurisdictions.

The officers and contributing authors of the power transmission and distribution committee are to be congratulated on their courage in presenting a symposium on a subject so controversial in nature as this one. The importance of the effect of differences in operating requirements and engineering design practices on distribution costs has been emphasized in the presentations. It is to be hoped for that this session will provide the necessary stimulus to distribution engineers so that the attendants at future Institute conventions will be able to derive the benefits of further thought and analysis of this problem.

William Shuler: In comparing the relative merits of the radial system with the primary network systems, there are 2 elements which are very important, one of which has already been touched upon, but the other has not been mentioned.

The possibility of improving the reliability of the radial system has been mentioned, but I do not think sufficient emphasis has been placed on this point. The interconnection of the lightning arrester ground with the secondary neutral apparently benefits the whole line performance rather than just the transformer; that is, with these lightning arresters, interconnected, there will be fewer flashovers on the line itself than when the arrester ground is separate.

Furthermore, we have made marked progress in improving our line construction. Also, the improvements in operating practices, such as high-speed relaying and instantaneous reclosure, are all tending to give to our radial system a degree of continuity which, in some cases, might be superior to a primary network. I am referring to the fact that in such a set-up, the dip in voltage on a radial system relayed for instantaneous tripping and closing may, as a matter of fact, permit customers' apparatus to continue in operation where the prolonged dip necessitated by network relaying might cause an outage.

The other point I wish to emphasize is that we must undoubtedly look forward

to the use of higher voltages for distribution circuits. When the time comes for making such a change, there will be less expense involved on systems employing radial distribution, than there would be where primary network installations have been made. I think, in the past, a great many of our decisions regarding fundamentals in system design have been made without giving sufficient weight to this point. Surely, our experience has demonstrated that the constancy of change confronts our industry to a greater extent possibly than any other.

Fundamentals of Design of Electric Energy Delivery Systems

Discussion of a paper by J. Allen Johnson and R. T. Henry published in the December 1933 issue, p. 831–8, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 489–95.

J. A. Johnson and R. T. Henry: The discussion of this paper, together with the other papers presented in the symposium, indicates the need of extreme care in making comparative studies to avoid drawing unwarranted conclusions from comparison of systems which are not truly equivalent. Much of the confusion which has existed, and still exists, could be avoided if more attention were paid to the fundamentals involved and if greater care were used to recognize differences between the operating characteristics of the systems compared.

In the latter part of D. K. Blake's discussion he states that for a large area the network will save money on cable and conduit, substations and even on transmission cable. We feel that this is not necessarily true. The principal factor in determining the ratio of "spare capacity" to "firm rating" is the probability of failures in the subtransmission circuits. A network with a low ratio of "spare" subtransmission circuits is not necessarily equivalent in reliability to a radial system with a higher ratio of spare circuits. While it is true that in the Buffalo system each group of subtransmission circuits depends entirely on the circuits within that group for spare capacity, it is a fact that in a large network the number of subtransmission circuits available as reserve for any particular subtransmission circuit is quite limited, unless excessive "interleaving" is provided. This is one of the elements of the problem which is not readily apparent in studies of small networks and it is much more apparent with 22 kv than with 13 kv subtransmission. In its practical effect it means that a network must have about the same number of subtransmission circuits and in turn about the same total transformer capacity as a system like the one in Buffalo in order to make it truly equivalent to such a radial system.

W. R. Bullard's suggestion that the subtransmission voltage be used as the primary voltage may result in very real economies but we believe it is not generally applicable.

In Buffalo, at least, local ordinances do not permit the use of overhead lines of such voltages, and there are many other objections to such a practice which will occur to anyone familiar with the subject, but which cannot be adequately discussed here. At present its principal field of application would seem to be in high density areas using underground feeders and low voltage networks, and in very low density areas (rural lines) where the higher voltages have been found less objectionable for overhead use.

John S. Parsons suggests that the use of aerial cable will materially decrease the cost as compared with underground subtransmission but we feel that the aerial cable also has only a rather limited application. It probably would not help the situation in Buffalo where there is a very definite program for the removal of overhead wires from city streets and where there are no alleys available.

Mr. Parsons also mentioned the advantage of air blast on the network transformers in order to provide emergency capacity. Air blast will undoubtedly provide emergency capacity in transformers but it will not help underground cables and is therefore of limited value in a network system where the subtransmission capacity is one of the controlling factors.

C. A. Corney raised several questions regarding the studies made in Buffalo. In these studies various sizes of network transformers were considered, including several different sizes between 1,500 and 4,000 kva. Double network units were also considered. The figure of 10 per cent which was published in the *Elec. World* in July 1931 was based on earlier studies with large network units whereas the figure of 36 per cent given in our paper was based on more recent and more detailed studies with 1,500 kva network units. These later studies were made principally because of suggestions that the use of smaller units would be more favorable to the network than the larger units considered in the earlier studies.

It is of interest to note the striking similarity between the system employed in Somerville with double unit substations and without tie feeders between substations which our Boston friends seem to identify with a primary network, and the system used in Buffalo which we call a radial system. Possibly the definitions suggested in our paper should be extended to include definitions of a "primary network" system and a "radial" system. There seems to be a tendency for some to identify the radial system with large substations and large transformer units and to call any system using small transformer units a network system. There appears to be general agreement as to the economy of small units. The point at issue, therefore, as between the two systems is whether it is better to group these small units and make the distribution feeders radial or disperse the units and interconnect them into a network through the distribution feeders.

We feel it will be helpful in arriving at correct conclusions if, in further studies and discussion of this subject, these fundamentals be kept firmly in mind.

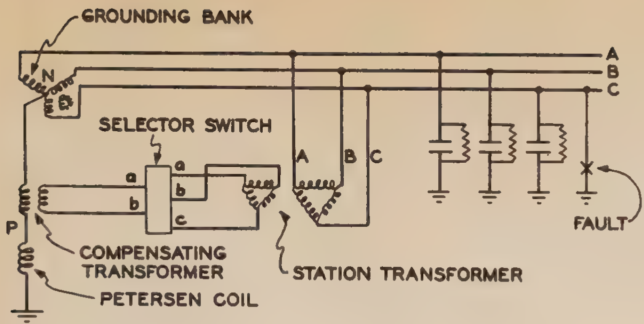
Petersen Coil Tests on 140-Kv System

Discussion of a paper by J. R. North and J. R. Eaton published in the January 1934 issue, p. 63–74, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 462–5.

J. R. Eaton: In the tests described in the paper it was found that corona and other system losses caused a fault current of approximately 45 amp, which could not be balanced out by the Petersen coil. On the assumption that losses in the system during fault would be proportional to the length of connected transmission line, it was anticipated that in case the Consumers Power Company 140-kv transmission system consisting of over 800 miles of overhead line were to be tied into one Petersen Coil system, the losses would produce a fault current of approximately 200 amp. With no definite information at hand, the question arose as to whether arcs of this current magnitude would be self-extinguishing. A method was worked out in 1932 which provided for compensating this loss current, thereby reducing the current in the fault to a very low value.

A schematic diagram of this loss compensating arrangement is shown in Fig. 1. The additional equipment required is a compensating transformer connected between the grounding bank neutral and the Petersen coil terminal, and a selector switch by means of which the compensating transformer may be energized from any desired phase of the transmission system. With a fault on phase C as shown in the diagram, the compensating transformer is connected to phase AB, the voltage E_{ab} is then added to the voltage between the transformer neutral and ground E_{ng}, giving a total voltage across the Petersen coil of E_{pg}. As current through the Petersen coil lags its voltage 90 deg, the current in the Petersen coil assumes the position I_p. By a suitable choice of the ratio of compensating transformer and the proper tuning of the Petersen coil, the horizontal component of the Petersen coil current may be made equal to the charging current I_c, while the vertical component of the Petersen coil current may be made equal to the loss current due to corona I_{cor}. Under these conditions the current in the fault would theoretically be zero. Obviously with this arrangement, a relay scheme must be provided which will cause the selector switch to apply to the compensating transformer a voltage taken from between the 2 unfaulted conductors.

On January 7, 1934, this scheme was tried out on the Petersen coil system described in the paper, making use of equipment available in the Saginaw River substation. Calculations showed 40 kv to be required for complete loss current compensation. However, the facilities available for test permitted obtaining a maximum potential of only 29 kv. In Fig. 2 is shown the results of these tests. The upper curve shows the current in the fault with the Petersen coil system operating normally. With the



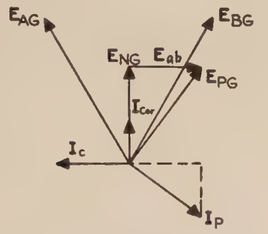
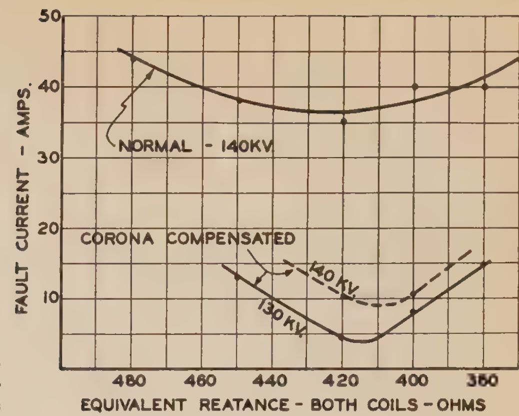
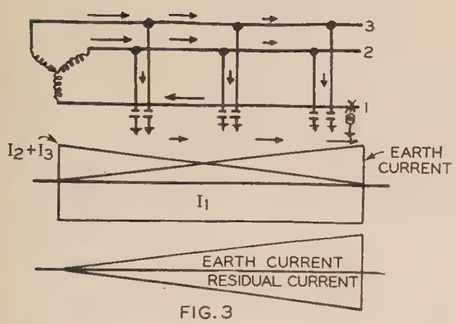
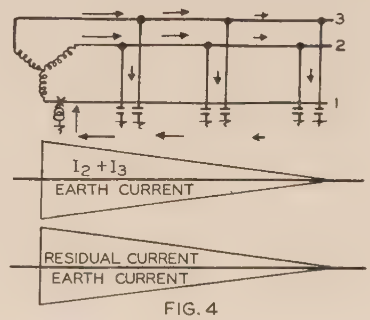


Fig. 1 (left and above). Arrangement for compensating loss current

Fig. 2 (right). Petersen coil system fault tuning tests



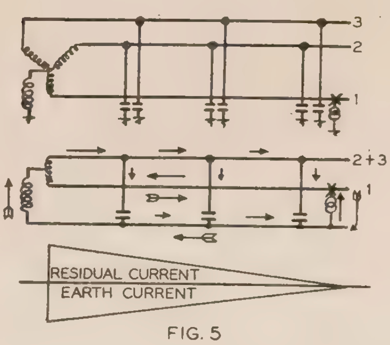


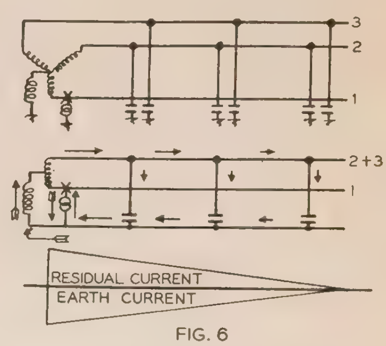


Figs. 3 (left) and 4 (right). Isolated neutral system

corona compensating scheme in effect, the fault current was reduced from 35 amp to 10 amp. At 130 kv the corona losses were considerably reduced and the loss current was almost completely compensated by the current through the Petersen coil. The remaining 5-amp fault current was of higher harmonic characteristics.

In general, the scheme performed as anticipated, and apparently affords a method of holding ground fault current to a low value regardless of the magnitude of system losses due to corona or other causes.





Figs. 5 (left) and 6 (right). Petersen coil system

J. M. Dunham: The authors have pointed out in their paper that the information given in Table IV, p. 69 (Electrical Engineering, January 1934) on the relative magnitudes of voltage induced in exposed telephone lines is applicable only to this particular system with a fault at Alcona. Some further discussion of these relative magnitudes with particular reference to the distribution of residual or earth current, for several types of grounding, may be of interest.

The distribution of residual current for faults to ground on an isolated neutral system is shown in Figs. 3 and 4. In Fig. 3 the fault is assumed at a point remote from the generating source and the residual current appears as a maximum at the point of fault dropping to zero at the source. If the fault occurs at the source, the residual current is again a maximum at the point of fault but is 180 deg out of phase with that for the previous fault location.

Considering the same system as above but connecting a Petersen coil in the neutral, the residual current distributions for faults at the source and at the end of the line are shown in Figs. 5 and 6. For simplicity, only the reactance offered by the Petersen coil and the capacitance to ground of the lines will be considered. To simplify the analysis of these circuits further, 2 currents will be considered, namely, that due to the presence of the Petersen coil, neglecting the capacitance to ground and the capacitance current neglecting the Petersen coil. These currents are then combined to give the residual current distribution. In this system the distribution of residual current is identical for both fault locations; in fact it is independent of fault location.

The measurements of induced voltage from which Table IV of the paper has been prepared are, of course, proportional among other things to the earth current in the exposure. In Figs. 3 and 5 it can be seen that if an exposure is located near the fault, the induced voltage for the isolated system will be greater than for the Petersen coil system. If, however, the exposure is near the source, the induced voltage will be greater for the Petersen coil than for the isolated system. Similarly the induced voltage will be affected by the location of the exposure if the system is grounded through a high neutral resistance. It is apparent from the above that the location of the exposure will exert an effect in determining whether the induced voltage will increase or decrease, in changing from an isolated neutral system to a Petersen coil or high neutral resistance system.

Table IV shows that the induced voltage for the Petersen coil system is less than that for the isolated neutral system, which follows from the fault and exposure locations. The grounding bank condition, for this particular fault location, is equivalent to a Petersen coil system about 50 per cent undertuned and the value of the induced voltage would be expected to fall between that for the isolated system and the Petersen coil system as shown in Table IV. With the system grounded through resistance (about 800 ohms) the induced voltage was higher than for the isolated neutral system. Although the total fault current is less in this case than with the system isolated, the effect of the neutral resistance is to change the distribution of earth current so that a larger percentage of the fault current appears in the exposure.

C. L. Fortescue: The Petersen coil has a vogue in Germany where I think it is safe

to say that there is not a single important transmission line which is not provided with Petersen coils for protection against outages. During my short stay in Germany for the World's Power Conference, I heard commendatory statements regarding the performance of the Petersen coil from all sides. However, it must be remembered that lightning storms are relatively infrequent in Germany as compared to what we get in this country. Nevertheless, according to my recollection, ground wires are in general use and the Petersen coil may be said to supplement the protective effect of the ground wires.

It is my opinion that the Petersen coil will undoubtedly have small application in this country, this application being for lines below 110 kv rather than for high voltage lines. Present information indicates that a 132-kv line with 2 overhead wires designed along modern lines will give practically as good performance from an outage standpoint as the authors' 140-kv lines with Petersen coils. A report by the Great Lakes Division of N.E.L.A. made on the performance of 132-kv lines equipped with 2 ground wires covering the Great Lakes District indicates an average performance over 5 years of the order of $1^1/_2$ outages per 100 miles per year, which it must be admitted is a very fair performance from a line outage standpoint. Lines are being built in the 230-kv class and higher from which a performance of one outage every few years per 100 miles of the line is expected. It is hardly to be expected that the addition of Petersen coils would substantially improve such performance.

A point I wish to emphasize is that the Petersen coil does not protect the apparatus from lightning, whereas a well designed overhead ground wire system is also excellent protection for the substation. As I have pointed out in lightning discussions in the past, the surge passing to ground through the towers from the ground wires does not materially involve the line wires; that is to say, the surge appearing on the line wires after the lightning surge has been dissipated in the ground is exceedingly small and is negligible as far as the substation apparatus is concerned provided that no failure of the line insulation takes place. In other words, the effect of the ground wires is to localize the stress due to lightning so that beyond the few towers that are affected by the direct lightning stroke a surge of only a moderate magnitude will travel over the line. The purpose of the Petersen coil is merely to prevent a lightning surge which may flash over a line insulator from developing into a fault to ground and it must be admitted that it performs this task with a fair degree of efficiency when in proper tuning and when corona losses are not excessive.

It would appear that the most favorable field for application of the Petersen coil in this country is on lines for rural distribution of power. These lines are usually simple single circuits and Petersen coils can easily be designed to operate with such lines. In these lines it is generally found that an adequate ground wire protection is uneconomical. In such lines while a number of lightning strokes terminate on the line and produce a large number of flashovers, the Petersen coil will insure that the majority of these flashovers will not become outages and the customer's service is not substantially impaired as a result of lightning. However, the Petersen coil has rivals which perform this service just as effectively. I have in mind, for example, the deion tube which not only prevents the lightning stroke from becoming an outage but also reduces the duty on arresters and other protective devices. For more complex circuits there may be developed the high speed circuit breaker with automatic quick reclosing means. This device can be used with the higher voltage transmission lines to supplement the overhead ground wires. It may be expected that with this device even the few outages that may occur as a result of failure of the line insulation will probably have a duration of not more than a fraction of a second and customers receiving power from the line will be inappreciably affected by it.

It is probable that except when horizontal construction is used with the line conductors spaced a long distance apart a considerable percentage of all lightning strokes to an exposed transmission line will involve more than one wire in which case, of course, the Petersen coil is powerless to prevent a phase-to-phase outage. The properly designed ground wire system will shield the transmission lines so that the likelihood of 2 phases of the conductors being involved is quite remote even when insulation failure does take place. It should also be noted that deion protectors or high speed reclosing breakers are effective against double line-to-ground or line-to-line flashovers, whereas the Petersen coil is limited to single phase-to-ground flashovers.

To sum up, I feel that while the Petersen coil may have a field in our systems it will not take the place of the good line protection which has been developed to a high degree within the last few years. You have all heard a great deal about making lines lightning proof. The reason that so much effort has been expended along these lines is that when the lightning-proof line has been achieved such a line can be loaded up nearly to the static stability limit without fear of instability and firm power may be sold to a customer over a single transmission line without having another line reserve to insure continuity of service. Thus the investment in transmission in lines will be very materially reduced for the same delivery of power.

J. R. North: J. E. Clem's explanation of the meaning of the term "zero sequence capacitance" is correct and in the definition of the term "Cg" given in the appendix, the words "with one conductor grounded" are unnecessary.

As C. L. Fortescue has pointed out, Petersen coils would have little application on systems consisting entirely of lightning-proof lines. However, there are many cases where Petersen coils would be applicable on systems where lines, because of structural, economic or other limitations, will not be equipped with ground wires or Deion tubes.

Messrs. Schnyder and Sidler in their discussions have mentioned the possibility of operating with lines grounded. In this country, it is generally customary and desirable to take out of service, as rapidly as possible, high voltage circuits which have become permanently faulted, irrespective of the method of neutral connection. This requires that means be provided for the proper selection and disconnection of the circuit involved and the problem becomes complex where several ground fault compensating coils are installed on a metallically interconnected system network.

Mr. Sidler has suggested the use of the term "Extinction Coils" rather than "Petersen Coils." In the paper on page 64 under the caption "Theory of Petersen Coil Operation," it is explained that a Petersen coil is only one form of ground fault compensating coil. This latter term has been used in several other places in the paper and the nature of the analysis outlined in the appendix is, as stated, a general one and is not limited to Petersen coils. Furthermore, it is felt that the term "Ground Fault Compensating Coil" is the proper term for such devices since it is more descriptive of actual operation as the coil tends to compensate the charging current to ground and the arc then becomes more or less self-extinguishing.

With regard to dissonance tuning, analyses and tests have shown that satisfactory operation of these Petersen Coils does not require 100 per cent tuning, and this is illustrated by Fig. 4 in the paper. As a matter of fact with a practical coil the taps are selected to cover certain increments of line and in many cases the coils may be operating slightly off tune due to the fact that the theoretical in-tune point of the system setup is between two tap positions. The unbalance current flowing in the neutral under normal conditions is extremely small. The tuning of the coils, contrary to certain expressed opinions, is very simple and may be easily determined by calculation or by test.

The statement referred to on page 70 of the paper to the effect that Petersen coils are only effective for clearing momentary faults is true without regard to the continuous current rating of the coil since by definition faults are cleared only when they no longer exist.

Automatic Reclosing of Oil Circuit Breakers

Discussion of a paper by A. E. Anderson published in the January 1934 issue, p. 48–53, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 466–7.

Robert Treat: A. E. Anderson has called attention to a matter which should be of vital interest to many operating companies. At a time when the utilities are under fire from so many directions, anything which permits even a minor reëstablishment of public esteem is of importance. Not a minor, but a major improvement in service is possible in many cases by adopting the operating procedure described.

Some pioneering spirits in a few operating companies have demonstrated by actual experience on their own systems that:

1. It is entirely feasible to reclose *im-*

mediately a breaker which has been tripped automatically, and about 9 times out of 10, the circuit has cleared up so the breaker stays in.

2. Customers who have made necessary modifications in their control equipments, ride through the 9 short circuits in which immediate first reclosure is successful with so little effect on their operations that they are not even aware that there has been a disturbance.

Thus, so far as the customer is concerned, by this simple and inexpensive modification in operating procedure, the power company eliminates 9 interruptions out of 10.

Certainly this is no general panacea for all interruptions. The nature of some loads is such that a 15-sec or even a 2-min outage is of no great concern. The nature of other loads and drives is such that possibly they cannot be benefited—at least with equipment now available.

One company, wishing to gain experience with immediate reclosing, decided to make a trial installation on 1 or 2 circuits. The first feeder selected was found upon investigation to average about one interruption a year, and the loads served by it were such that an outage of 15 sec, or even of 15 min, was of no consequence whatever. Obviously, it would require a very enthusiastic person indeed to justify the application of immediate reclosure to this feeder.

However, experience has demonstrated that many types of load can be benefited by immediate reclosure. Utilities having such loads, if they are now subject to too frequent interruptions cannot afford to overlook this important means of regaining some lost public favor by furnishing greatly improved service.

It used to be felt that the one way of assuring continuous service to important loads was to provide 2 feeds. This does help, especially if the 2 feeds are from separate sources, and supported on different structures. However, experience has shown that 2 overhead circuits on the same pole or tower are sometimes not sufficiently immune to simultaneous troubles as to guarantee the desired degree of freedom from interruptions. One company reports that it has a double circuit line, on which 10 per cent of the outages involve only one circuit, 90 per cent both circuits. It is entirely conceivable that sometimes a single circuit line provided with immediate reclosure may give fewer interruptions to loads that can take advantage of it, than a double circuit line can without immediate reclosure.

D. W. Ellyson: The Kansas City Power and Light Company has been operating automatic reclosing oil circuit breakers on a 15–30–75 sec cycle since 1922, and at the present time the following breakers are in service:

255	Single-pole 2,540/440 volt Y (one for each phase)
24	Single-pole 6,950/11,950 volt Y (one for each phase)
1	Three-pole 13,500 volt
6	Three-pole 19,050/33,000 volt Y
286	Total

Our experience has been that these reclosing breakers give better service than was obtained from the manually operated stations and that they have materially reduced the time required to restore service. A summary of tripouts of 2,540/4,400-volt Y, oil circuit breakers from April 1926 to November 1932 showed a total of 424 tripouts divided as shown in Table I.

The percentage of lockouts is 13 per cent, which is considerably higher than the figures shown in Mr. Anderson's paper. This may be due in part to the fact that our figures were obtained from regular log sheets where all the lockouts are carefully noted but in cases of general trouble it is possible for the dispatcher to overlook a breaker opening and then closing and remaining closed.

From an examination of these figures it is seen that in 77 per cent of tripouts the breaker remained closed after the first reclosure. If instantaneous first reclosing had been used, it would have in effect cut out 77 per cent of the outages, as the great majority of the load is lighting, and all the customer would have noticed would have been a dip in his lights. This lead to the adoption of instantaneous first reclosure on all the 19,050/33,000Y outgoing circuits for our new 13,500–33,000Y step-up transformer substation.

This includes a total of 7 equipments, 2 transfer breakers, 3 for radial feed circuits and 2 for feeding a 19,050/33,000Y loop, so that our entire 33,000Y load is handled by instantaneous first reclosure breakers.

The final installation of these breakers was made only a few weeks ago so that we do not have any operating data to make any comments on just what will occur. However, we did have one case where a cat short-circuited the 33,000-volt bus in the loop station containing the sectionalizing breaker, and this breaker and one of the loop breakers at the substation opened, killing one section of the loop, and then both breakers reclosed instantaneously. A coal mine using one 500 hp and one 800 hp shovel was in operation at this time and the operators did not know that our breakers had opened.

Our equipments require approximately 55 cycles (determined by means of a cycle counter) from the time the main contacts break contact to the time they make contact again.

Due to the fact that the synchronous motors connected to our lines are of relatively small capacity as compared to the lines which feed them, we have not at present had to take into consideration any possible feed-back to the short circuit from synchronous equipment. However, there is a cement plant connected to our lines and having synchronous motors of rather large capacity, and the breakers supplying these motors have been equipped with low voltage devices that trip these breakers before the instantaneous breakers have time to reclose.

Table I—Summary of Tripouts

	Breaker Remained Closed After							
	1st Recl		2nd Recl		3rd Recl		Lockout	
	No.	%	No.	%	No.	%	No.	%
Total single-phase	180	42.4	31	7.31	4	0.94	31	7.31
Total 2-phase	117	27.60	4	0.95	0	..	12	2.83
Total 3-phase	31	7.31	1	0.24	1	0.24	12	2.83
Grand total	328	77.3	36	8.50	5	1.20	55	13.00

A. E. Anderson: E. E. George points out advantages that have been experienced where certain large synchronous motors were operating in conjunction with induction motors, all being installed in the same plant. Although the synchronous motor (after a power interruption) tends to maintain normal voltage, which will delay the dropping out of instantaneous undervoltage devices, this same characteristic will also tend to maintain arcs on the feeder system. As pointed out in the paper further operating information is required before the overall effect of the synchronous motor can be evaluated for general application.

H. A. P. Langstaff describes the extended application of a-c reclosing equipment to tie-lines on the system of the West Penn Power Co. where 137 equipments operate as stub feeders (44 on interconnections) and 33 equipments operate when the line is energized from the other end, resulting in approximately 20 per cent of the equipments on this system, functioning as multiple feeders.

Another important item referred to is the proper coördination of fuse and relay characteristics, which is essential if the equipment is to give the desired degree of selectivity required for system operation.

Mr. Langstaff concurs with Mr. George in the opinion that a third reclosure is a decided advantage. As pointed out in the author's paper, the third reclosure can be obtained in the conventional design of a-c reclosing relay, with practically no additional expense or complication.

In the case that Mr. Langstaff cites, illustrating the possible application of automatic reclosing relays (to an attended station) the number of outages per year was extremely small. However, there are many installations where service requirements or a sufficiently large number of operations warrant the installation, in attended stations, of a simple relay of the type shown in Fig. 5, giving one immediate reclosure, followed by one or two reclosures under the control of the station operator.

The data submitted by Mr. Ellyson, covering the period from April 1926, to November 1932, gives a higher percentage of lockouts as compared with the values in the author's paper. Mr. Ellyson gives one possible explanation for this higher value. It has been noted that faults on an underground system are more often of a permanent nature as compared with those on overhead systems. When systems of the latter type are installed in localities subjected to frequent thunder-storms, the percentage of lockouts would presumably decrease, due to the transitory effect of the

disturbance. Other transitory disturbances would also tend to decrease the percentage of lockouts.

Lightning Measured on 4-Kv Overhead Circuits

Discussion of a paper by Herman Halperin and K. B. McEachron published in the January 1934 issue, p. 33–7, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 465.

Edward Beck: The paper by Herman Halperin and K. B. McEachron is timely and important because here are presented for the first time field test data on a distribution system. The writer agrees with the order of the lightning arrester currents mentioned by the authors for this system, but we would like to point out that even on this system higher currents may occasionally occur. The probability of this occurrence appears to be so low that the authors consider it negligible. Certain observations and experience indicate that on some distribution circuits the occurrence of surge currents of several thousand amperes is not negligible, and that currents of the order of 80,000 to 100,000 amp are possible although very rare.

Of considerable interest in the paper are the results secured on transformers with interconnected lightning arresters which show the considerable benefits to be secured by the application of protection around the transformer thereby limiting the voltage which may be applied across the transformer to the lightning arrester voltage even though the potential from the primary leads to ground may be of considerable magnitude as indicated in the authors' Table II. Of further interest in this table is the fact that the field tests produced records of the voltage across interconnected transformer and therefore across the lightning arrester itself which are in good agreement with the voltage measured across terminals of lightning arresters in laboratory tests.

With increased attention being given to the reliability of distribution circuits, the collection of data of the kind presented by Messrs. Halperin and McEachron is very valuable and it is hoped that this paper will stimulate further investigation by others, particularly on some exposed rural distribution lines.

C. L. Fortescue: This is the first case of a systematic investigation of surges on distribution circuits that has ever to my knowledge been carried out. While the tests have resulted in a large amount of statistical data on low potential surges that occur on distribution lines, the set-up was such that potentials above 500 kv would not be recorded because they would cause flashover of the potentiometer used in connection with the surge recorders. In like manner, large surge currents through the lightning arresters would not be recorded because an instrument and potentiometer to record the potential of the surge always accompanied these installations.

If we consider a section of distribution line 0.5 mile long, the probability of strokes above 2,000 kv terminating on the line within this section is only about 0.15 per year or about one every 7 years. The probability of strokes of 8,000 kv and above is about $^1/_{10}$ of this or 0.015, about once in 70 years. In considering the possible potential that may arise on such a line due to being hit by a stroke of lightning, the resistivity of the earth and the resulting resistance at the pole must be considered. The probability of strokes of the order of 20,000 kv terminating in the half mile section is about 0.003 per year and the probability of a particular transformer in this half mile section receiving such a stroke is still smaller, being probably of the order of 0.0002 per year. If there are 1,000 such sections, each containing a transformer, the probability of a transformer receiving such a stroke is of the order of one every 5 years out of the 1,000 transformers. If the value of current due to such a surge will destroy an arrester and both arresters will be involved, and if there are 1,000 transformers with neutral connections each using 2 arresters, about the same number, namely, one out of 1,000 every 5 years, will be lost.

The above figures are rough and simply indicate the order of the magnitudes encountered and apply to suburban circuits. The presence of a large number of guyed poles will materially reduce the hazard to transformer and lightning arresters due to lightning, and the hazard will be much less for urban lines. They, however, show how small is the probability even in 4 years testing of obtaining high potentials in the sections where measuring instruments were installed.

The idea quite generally held that the flashover of the line insulation including wood poles determines the magnitude of the potential of the surge on the wires is erroneous except when the footing resistance is very low. In some parts of the country footing resistance may reach values of several hundred ohms. Under such circumstances, most of the potential appears locally in the earth. I think that pole shattering due to direct strokes will take place whenever a severe lightning stroke hits a pole, but it will be more severe where the footing resistance is low, and the extent of travel will be reduced. A pole having a length of 40 ft between ground and cross arm has a probable minimum flashover under long surges of about 2,000 kv. It probably begins to flash over at this value even with steep waves but complete breakdown does not occur probably for 8 or 10 μsec at this potential. At higher potential, breakdown is accelerated but the surge potential will have time to build up to considerably higher potential than 2,000 kv before the complete breakdown takes place. With high resistance in series with the pole complete breakdown may never be reached because the small current required to raise the potential of the ground will be readily supplied by partial breakdown of the wood pole, and, therefore, the pole top potential will be high and the surge will be propagated over the line with attentuation due to corona and also due to partial breakdown to the high resistance ground at each succeeding pole.

It should be evident, therefore, that the test reported in this paper includes none of the surges that is likely to injure transformers or destroy arresters, as the potentials recorded are not sufficiently high and should be well within the capacity of even the poorest types of lightning arrester.

I was fortunate enough to witness a direct stroke to the distribution line supplying my house a couple of years ago. I was outside on the veranda watching the lightning storm when the stroke took place about 2 blocks from my house. Streamers issued from all the wires for the full length of the 2 blocks, of the type encountered in the laboratory and known as suppressed discharges. The pole these discharges appeared to enter showed evidence of surface corona at spots along the pole. Unfortunately, this stroke happened in daylight and the full extent of corona over the pole surface was not visible, but the streamers issuing from the line wires would indicate a value of the surge traveling over the wire of at least 1 or 2 million volts and the surge was evidently sharply suppressed by the discharge to ground. The station circuit breaker opened and the telephone cable on the same poles was injured putting the telephone service out of commission until repairs were made.

My conclusion after reading the paper is that the majority of surges recorded in these tests are induced surges which would be expected to be large in number. The higher potentials that were encountered may have been due to side flashes or small strokes which may have been reduced in magnitude due to having occurred near an arrester. To give due credit to the authors of this paper, it must be pointed out that this data which they have procured are the statistical data that are lacking in our lightning statistics and while this type of surge is not likely to cause outages or injury to apparatus, it is likely to be the cause of other troubles not so serious from the operating company's point of view but which on account of its frequency of occurrence must be considered.

J. K. Hodnette: The authors have presented some interesting data on the voltages and currents produced in low voltage urban distribution circuits by discharges of lightning. They form a valuable indication of the frequency of occurrence and approximate magnitude of surges in these circuits.

From the data obtained, the authors have reached the interesting conclusion that the surge currents usually expected on urban circuits are 300 amp or less and the surge voltages considerably less than 200 kv. These values agree with the general conception of the values that would be expected for induced surges in metropolitan districts where the lines are largely shielded by buildings and other tall structures and where direct strokes are indeed improbable. However, the same does not apply to distribution circuits in general as evidenced by the fact that on the short, 1,600 ft, sections of exposed line, the authors obtained 82.5 per cent of their measurements of voltages in excess of 50 kv. On rural and village lines, the expectation of high surge voltages would be increased as well

as the frequency of occurrence. Also on such lines direct strokes would be expected to occur more often.

Two years' field experience with several thousand distribution transformers with lightning protection around the transformers, on lines throughout the country have indicated that high surge currents occur relatively often (See "Heavy Surge Currents—Generation and Measurement," P. L. Bellaschi, ELECTRICAL ENGINEERING, January 1934, p. 86–94). This experience is not interpreted as establishing the probability of direct strokes on distribution circuits on account of the diversity of locations, etc. It does indicate, however, that each year approximately 0.5 per cent of such transformers are subjected to very high surge voltages, or their protective devices to surge currents many times higher than those measured by the authors.

In addition, a direct stroke does not have to hit the line very near a transformer to give rise to these high currents. High surge currents may be conducted along the line for a relatively long distance—possibly as far as 1,000 to 2,000 ft under usual conditions of line construction and ground resistances. Although the enormous voltage attending a direct stroke of lightning on a line is sufficient to flash over the pole insulation, where the ground resistance at the base of the pole is high, a voltage of high magnitude will still remain on the line until it is shunted to earth by other contacts or a low resistance connection such as the multiple grounds of a secondary neutral.

On exposed lines, as indicated by the above field experience, heavier surge currents than these indicated by the authors must be taken into account.

Herman Halperin: The experience in Philadelphia, as reported by H. N. Ekvall, gives further evidence of the operating and economic advantages of the use of the interconnection in urban territory. For such applications, all available data indicate that these improvements obtain with no increased hazard to customers' premises and with no very serious accompanying disadvantages. The only disadvantage found in the Chicago experience was that with the interconnection, the rate of failure of arresters during lightning was about twice the rate for the arresters grounded only to a driven pipe. This increase means that with our complete use of the interconnection the number of arrester failures would increase from about 25 to about 50 per year. On the other hand, annual removals of arresters due to all causes in Chicago are several times these figures.

Referring to Mr. MacCarthy's remarks, while 2 high voltages, i. e., 30 and 37 kv were measured across the secondary lead of the transformers, the practically complete absence of troubles in customers' premises indicates that such voltages are not maintained for an appreciable time nor exist very far out on the services to the customers. In addition to his point that the lower rate of transformer failure near open ends of lines may be due to the smaller primary exposure for such installations, the lower rate could be due to the lower voltages that are incident to draining surge current from practically one direction as compared to the surge voltages that appear with surge current drainage for two directions. As Mr. MacCarthy remarks, with reference to Fig. 6 of the paper, conditions at the end of the line opposite the arresters shown may have affected the voltage distribution along the line. In reply to his inquiry, the distances to the nearest equipment, shown in Fig. 7 as 750 ft and 1,600 ft, also represent distances to the nearest arresters.

We agree with Messrs. Beck, Fortescue, and Hodnette that very high surge currents probably do occur on distribution lines—rarely in urban districts and more frequently in rural territory. It is interesting to observe that Mr. Fortescue's analysis of severe surge currents, apparently derived on a probability basis, is in good agreement with statistical records in Chicago. For transformer burnouts due to direct strokes about one transformer failure occurs per 200,000 transformers per storm, or roughly one transformer per 1,000 transformers every 5 yrs. The rate of failure of arresters installed in the normal manner, during thunder-storms has been about three failures per 1,000 arresters every 5 yrs. This, while somewhat higher than the figure given by Mr. Fortescue, probably includes also failures due to voltages lower than the values assumed by him, which are not only approximate, but also probably high. His statement that the surges recorded were not of dangerous proportions is questionable in view of test data and operating experience showing that many distribution transformers in service will fail at surge voltages of about 100 kv or even considerably less.

K. B. McEachron: As pointed out by Messrs. Beck, Fortescue, and Hodnette, direct strokes will be a more important factor in connection with exposed lines than it will be for unexposed circuits. This means that high impulse currents may be expected to be encountered more frequently on rural circuits than on those circuits where considerable shielding exists. That this is true in Chicago is shown by the comparison between the so-called "long" distribution circuits and the urban circuits.

The data obtained do not shed any light on the frequency of occurrence of discharges of great magnitude on rural circuits. Data of this sort should be obtained in order that the proper valuation may be placed upon the necessity for direct stroke protection on rural circuits. The experience with a large number of arresters on rural circuits does not seem to indicate that direct strokes of great magnitude are a predominant factor in rural protection. However, as I have already indicated, more data are necessary before any conclusions can be drawn.

I am somewhat surprised to note that Mr. Fortescue believes that none of the surges reported in the paper are likely to injure transformers. It is interesting to note in this connection that distribution transformers do fail in Chicago during lightning storms without any evidence of damage either to poles, cross-arms, or arresters. The very great reduction of transformer failures, due to interconnection, indicates clearly that most of these failures are not due to the inability of the arrester to perform its intended functions, but rather due to the circuit arrangements which permit the effects of ground resistance and length of ground lead to seriously influence the protection afforded the transformer.

With transformers and arresters in proper condition, it seems that it ought to be possible to reduce the number of transformer failures to those cases associated with severe direct strokes, in which the current magnitude is of the order of several thousand amperes.

It is to be hoped that statistical data, relating to the performance of arresters on rural circuits so arranged as to show the relation between pole damage and these failures, will be gathered and presented to the Institute, to help clarify this whole question of the requirements of protection for the distribution transformer.

Control of Distance Relay Potential Connections

Discussion of a paper by A. R. van C. Warrington published in the January 1934 issue, p. 206–13, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 465–6.

A. R. van C. Warrington: E. E. George is correct in his assumption that at present the automatic potential switching means described in the paper are not generally applicable for use with bushing potential devices.

Both Messrs. George and Neher brought up the point that the nature of the fault may change before the distance relays have operated which might result in incorrect distance measurement. The type of change which would necessitate a change in potential connections is the spreading of a single-phase ground fault to one or both of the other phases. The single-phase ground fault requires wye voltage while delta voltage is required for multiphase faults if residual current compensation is not employed as in Fig. 5. In Fig. 8 residual current is added when the relay is supplied with wye potential, and the zero sequence component of the current eliminated during multiphase faults, so that the distance relay operation is correct with either position of the transfer switch if the ground fault involves more than one phase. In Figs. 9 and 10 wye voltage and residual-compensated current are supplied to the distance relay on all ground faults regardless of the number of phases involved.

Mr. Neher has pointed out that distance relays in which the ohmic and starting units are supplied with potential from different phases will require separate switching for the two units. This means duplicate contacts on the switching relays in Figs. 1, 2, and 3, which would therefore seem more applicable to distance relays with single-phase potential with amplifying means for insuring reliable operation on low voltage. Where 3 relays are used for phase and for ground faults (Figs. 5, 8, 9, and 10) there are 2 alternatives. Either single-phase potential can be used or the ohm units only can be switched, their starting units being supplied with excitation suitable for response to both interphase and ground faults.

Portable Schering Bridge for Field Tests

Discussion of a paper by C. F. Hill, T. R. Watts, and G. A. Burr published in the January 1934 issue, p. 176–82, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 478–81.

F. C. Doble: The discussion of this paper by Messrs. Sporn, Gross, Balsbaugh, and others has been of great interest and constitutes a valuable addition to it. It is especially gratifying to have the Westinghouse Company put the stamp of its approval on power-factor and loss measurements as reliable indices of the insulating integrity of bushings and other insulation. Mr. Sporn referred to the work he has been doing for the last 4 years in service up-keep using the Doble power-factor test set. To complete the record it would be well to state that this test set and the method of field testing using power factor which was developed by the Doble Company was quite thoroughly described at a special meeting before the N.E.L.A. at Harvard University in April 1931. Again a paper was presented in October 1932, before the National Research Council in Baltimore covering the results obtained from 3 years of field service.

In designing the Doble power-factor test equipment some 5 years ago a great deal of thought was given to the selection of the design and type of apparatus to be used in order to get the maximum of practical results from field testing. It was decided to employ the wattmeter method and direct-reading indicating meters. Some difficulty was experienced at first in adapting the meters to this use because no existing instruments were suitable but a special solution was worked out which leaves very little to be desired from that standpoint.

In this connection it may be noticed that the wattmeter method measures directly and effectively the resistance values of wood members in oil circuit breakers. Here the variable resistance that is sometimes encountered introduces no difficulty because the direct-reading instrument is able to follow changes as they occur which is not the case with the bridge where it is necessary to get a reading by seeking a balance. This balance method requiring an appreciable amount of time is ill-adapted to follow up a constantly changing value even though the magnitude of the change be not very great.

As might be expected, the authors do not attempt this kind of reading with the apparatus which they describe but recommend the substitution of the megger for that purpose. There is another point which no doubt influences them also and that is the practical impossibility of making resistance measurements with this bridge as designed where the capacitances involved are extremely small as is necessarily the case with wood members.

In the field, high electrostatic effects are apt to be present. Such effects as they produce are, in the case of the wattmeter type of test set, effectively averaged out by taking additional readings with reversed source connections.

It seems as if the bridge would not lend itself so effectively to this means of eliminating objectionable inductive effects and, in point of fact, in the field such a situation is known to have arisen.

B. L. Goodlet: I notice that the work described in this paper is stated to be "probably the first application of the Schering Bridge to field tests."

I would therefore contribute the information that the company with which I am associated has employed a portable Schering bridge for field tests for something like 5 years.

The first portable Schering bridge was constructed by my firm in 1928, after several years' experience of power factor tests in the works had proved the value of the method. A photograph of this early instrument is reproduced in Fig. 1. The test voltage is 5 kv, the transformer and bridge being both contained in a single wooden box 18 × 21 × 17 in. The small box on the right is a ratio transformer to allow the bridge to be fed from any a-c supply from 100 to 500 volts.

This instrument was first employed in field tests carried out under my supervision in the London district in 1929, and has been in regular use ever since. The development has not to my knowledge ever been described in print but is alluded to on p. 17 of a paper "A Contribution to the Better Knowledge of Resin Paper Insulation" read by the writer at the last International High Tension Conference (Paris, June 1933).

Figure 2 of this paper (taken from a still earlier one) is the same as Messrs. Hill, Watts, and Burr's Fig. 6, while Figs. 3, 4, and 5 support their statement that the majority of bushing troubles are due to moisture entering the bushing.

For the last 5 years every paper bushing made in our works has been given a power-factor test at maximum rated voltage and temperature. Each bushing passed is marked with an identity number from which its manufacturing history can be traced. This information being available, the results of field tests can be immediately assessed. No trouble has been experienced since this practice was adopted.

I. W. Gross: The authors have summed up the bushing testing problem quite correctly when they say: "Dielectric loss measurements detect deterioration of insulation which might later cause failure." This principle was made use of in the portable insulation tester we have been using. In fact, the set reads "watts" and "current" directly, and from these values the power factor is obtained by one setting of a slide rule, since the applied test voltage is 10,000 volts. In detecting defective conditions internal to the oil circuit breaker, we put entire dependence on the watts loss readings, and a correct interpretation of these easily locates trouble external to the bushings. It seems to us, if excess dielectric loss is the cause of insulation failure, a test set should, if possible, measure this loss directly and not measure everything except this loss.

The field technique of testing described by the authors, such as measuring power factor on oil circuit breaker bushings with the breaker open and closed, and testing transformer bushings with and without windings, we have been making use of ever since we first used the power factor method of test, that is, over a period of some 5 years. It is interesting to note that the authors suggest little in the way of improvement in test methods with their test set.

The idea of applying power-factor measurements to oil was, to our knowledge, first brought out for field use about 2 years ago. Since that time we have used this test repeatedly. Our experience has been that where defective insulation was found the oil frequently had a high power factor, although in some cases the oil has tested good on the breakdown test. It would be interesting to know what the authors' experience has been in this respect, and at what value of power factor they recommend reconditioning the oil.

There is one feature of power-factor testing on which the authors have placed some emphasis. That is, disconnecting the leads from an oil switch to the bus or disconnecting switch. Leaving the lead attached,

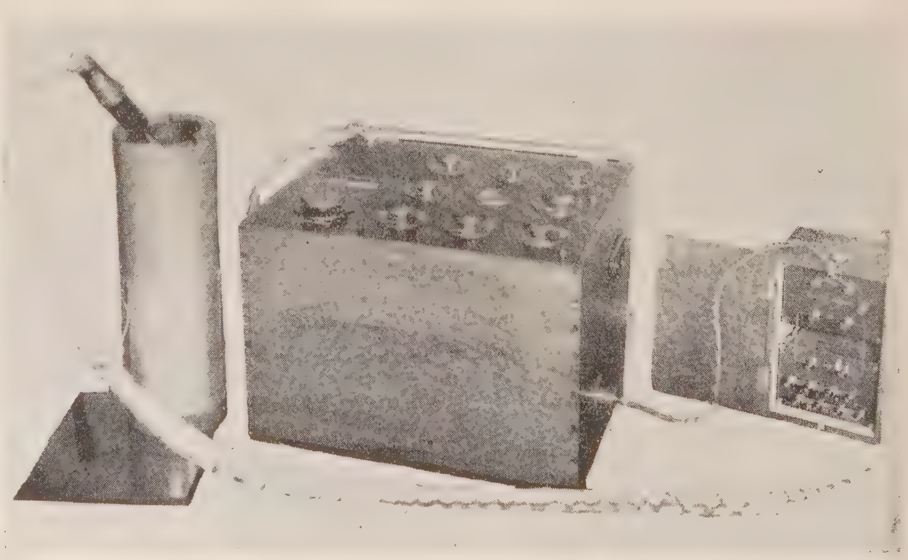


Fig. 1. Portable Schering bridge constructed in 1928

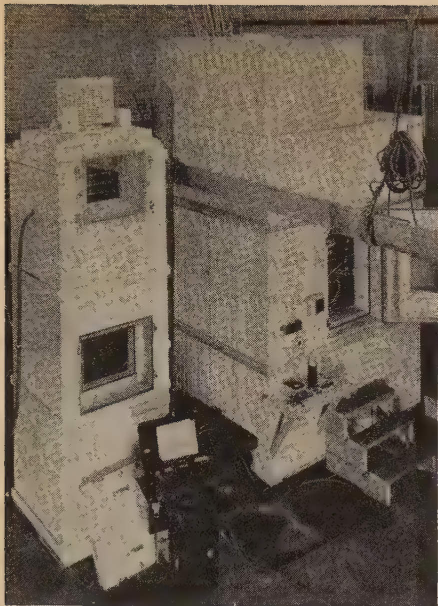


Fig. 2. Laboratory test set-up for determining bushing temperature-power factor characteristics

they claim "has disadvantages which lessen the value of the bushing test." We have found, on the contrary, that there are in most cases, distinct advantages in leaving the lead attached, provided the test set is capable of detecting defects under these conditions. With the lead attached all switch and lead insulators are included in the test circuit. We have, in some cases, actually found defective insulators by this method of test which would not otherwise have been found. Pickup interference due to this lead has never given us any trouble in our testing work.

It is also stated in the paper, that if the test is made with the lead attached, the bushing capacitance is not obtained, and that this should be watched as closely as the power factor. We have never used the capacitance characteristic of a bushing in any of our tests on condenser bushings to determine a bad bushing, although it is easily obtainable from the measured field current, and yet, we have been able to pick out defects in condenser bushings the same as in any other bushing.

One of the important features of bushing testing is locating the trouble. In testing some 15,000 bushings of all types, and over 2,000 oil circuit breakers, we have run down in detail a great many cases of trouble. One typical example may be of interest. An oil circuit breaker was found with bushings having a high power factor; and the insulating wood inside the breaker showed defective. In one bushing bad oil was found with 5.4 per cent power factor, but having a breakdown test of 31 kv. This oil was changed. A heavy carbon deposit was also found inside the breaker. Cleaning the inside of the breaker failed to remove all the trouble, so the wood guide and lift rod were checked for resistance by the power factor test set. One guide, in different sections of its length, showed a resistance from 21 to 270 megohms, while a corresponding new guide had 1,540 megohms resistance. The old lift rod had a resistance from 63 to 200 megohms, while a new lift

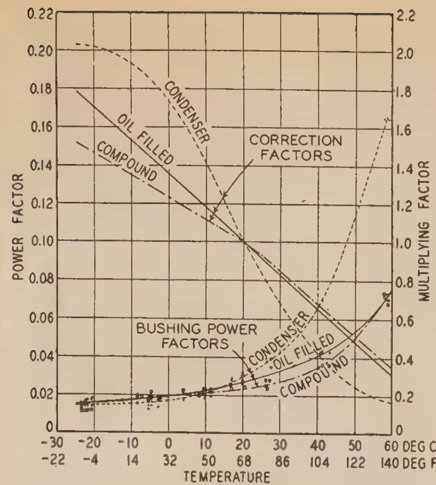


Fig. 3. Power-factor temperature characteristics of bushings

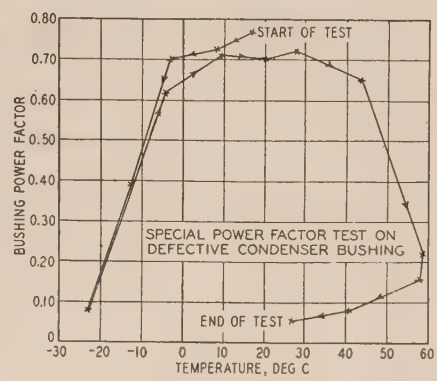


Fig. 4. Power-factor temperature characteristics of a very bad bushing

rod had 3,000 to 10,000 megohms. The old lift rods and guides were baked and finally brought back to a resistance of 2,000 to 10,000 megohms. These megohm readings were all taken on the test set, and not by the ordinary d-c instrument. Eleven months later, when the breaker was retested, the power-factor readings were normal, showing that the trouble which had been removed had not recurred. This type of detailed investigation in definitely locating and clearing up trouble is typical of some of the work we have done with the test set, beyond the mere routine testing of bushings.

Although our testing of transformer bushings has not been so extensive as on oil circuit breaker bushings, recent results indicate the desirability of testing transformer bushings, if costly failures are to be avoided. On one of our properties where systematic testing of transformer bushings has recently been started, out of 100 transformers tested, 11 "defective" conditions, and 7 "remove" conditions of insulation were found. This indicates faults considerably higher than the average found on oil circuit breakers, although the extent of the transformer tests is still too limited to draw this as a definite conclusion.

In carrying out our field testing through an entire year, we noted the power factor readings of bushings were affected by the temperature, but not sufficiently, at the time, to cause any concern. As the test work proceeded, however, and the test set had definitely proved its ability to find insulation faults, refinements in the testing technique were made. One of these was the determination of bushing power-factor values with temperature variation. Test equipment for this work was made available by the Doble Engineering Company, and several bushings of different types were obtained from the field and taken to the laboratory for detailed tests. The laboratory set-up for carrying on these tests is shown in Fig. 2. The bushings were enclosed in a cubicle and the temperature altered from −23 to approximately 60 deg C.

The power-factor temperature characteristics of the condenser, oil filled, and compound filled bushings tested are shown in Fig. 3. These power-factor curves have been converted to correction factors for use in reducing all field power-factor readings to a 20 deg C reference basis. Although the tests were carried out with care and precision, it is not maintained that the correction factors can be used indiscriminately as a hard and fast basis to eliminate temperature effects entirely on power-factor readings. Many more such tests will be required on a large number of bushings before an accurate average representative curve for each type of bushing can be obtained. But even then, it should be kept in mind that all parts of a bushing in the field are rarely at the same temperature, so that the data presented in the figure is probably sufficient for the purpose intended, which is, to correct observed power factors, on a practical basis, to a given reference basis.

In Fig. 4 is shown the power-factor variation of a very bad bushing as the temperature was lowered from 17 deg C to −23, then raised to 58 deg, and again lowered to 28 deg over a period of about 5 days. At the end of the test the bushing, which then had a power factor of 0.055, was flashed over once on 60-cycle test, but on the second application of voltage, the bushing punctured. The deduction we have drawn from this special test, as well as from field tests on other types of defective bushings, is that if the bushing is found very bad, it is doubtful if its insulation can be satisfactorily rejuvenated.

There are several points in the last 2 paragraphs of the authors' paper that are not entirely clear. The implication that a bushing with high power factor (that is, with defective insulation) will give satisfactory service, provided it has a somewhat higher voltage rating than the rated voltage of the circuit on which it is used, does not seem sound. We have found several bushings defective by the power-factor test in the field, which later successfully withstood a 60-cycle high voltage test, and then failed on impulse tests. Such bushings even though they have a voltage rating in excess of the circuit rating, are a potential hazard, unless their impulse strength is in excess of other nearby apparatus, or unless other protection to limit impulse voltages is supplied. Even where a defective bushing has a high rated voltage in comparison to the circuit voltage, such a bushing may fail in service if it is not carefully watched for rapid progressive deterioration. We believe bushings in the above class, except in rare cases, can be justly classified as a general nuisance on a power system.

The paper states "the number of faults will materially decrease with repeated tests." This is a rather optimistic general

conclusion. Decrease in bushing faults and failures is the goal of every operating man, but repeated tests to locate and remove insulation faults must also be supplemented by effective work in reducing the cause of the fault, if a worth while reduction is to be secured. While power-factor tests have demonstrated their ability to detect faults in existing bushings and similar insulation, we need, for the future, more careful thought and intelligent design in rendering such insulation immune to trouble, and serviceable under the conditions which must be met in service.

Philip Sporn: The authors state that "a portable instrument for the measurement of dielectric loss was not available for purchase and use by the power companies until the Schering bridge here described was developed." As a matter of fact the idea was first proposed and a test set made available some 5 years ago. Although the method was viewed with skepticism at the time, the situation today is entirely different. The power-factor method of testing bushing and similar insulation is now a generally accepted practice.

Bushing testing with a portable power-factor tester has been carried out on the properties of the American Gas and Electric Company system for the past 5 years. In Fig. 5 there are shown 2 views of the type of test set that has been employed. You will note the compactness of the set which includes a transformer, control panel, and test instruments. This test set was designed and built by the Doble Engineering Company. In Fig. 6 is shown the use of this equipment for testing bushings, in this case the test being made on a 33-kv transformer. In Table I is shown a summary of results of bushings tested in 1929. You will note that out of some 3,880 bushings tested there were found 122 cases, or 3.15 per cent, of faulty conditions. These, when further analyzed, showed 58 bushing faults totaling 1.5 per cent, and 64 external faults, or 1.65 per cent. Because of this comparatively large percentage of faults, and because of the damage that a bushing failure, particularly a failure of a bushing connected to the bus side of a high voltage heavy power bus invariably results in, it was decided to continue, and further develop, this method of testing. It was felt, for example, that when faced with a situation such as is shown in Fig. 7, which shows 7 44-kv bushings that failed on one property during one storm, or when faced with a situation of defective insulating material like the one shown in Fig. 8, which shows the bracing material and operating rod on a 66-kv breaker, that something more than merely replacement with another insulating member of the same kind, or something more than merely waiting until the actual damage occurred and then mopping up, was necessary. Proper operating and proper engineering dictated the digging down and finding out what was causing these troubles, and if possible, setting up standards for safe equipment and standards of unreliable and unsafe equipment, so that the unsafe equipment could be taken out, serviced, and replaced before the damage was actually done.

The extent to which the problem was studied can perhaps be seen by Fig. 9 and Table II which show diagrammatically the results of a study of a particular 44-kv bushing found in service with a power factor of 0.076. On the basis of previous standards established, it was found that this represented a poor insulating condition. The bushing was then dissected piece by piece and the results of this dissection, including the power factor and watts loss readings shown progressively in the table, until finally the defect was definitely located. The felt washers which were used between the individual skirts of the porcelain had absorbed moisture, and gave a power factor anywhere from 0.36 to 0.98. This wet felt had apparently resulted in moisture and other deleterious effects communicating themselves to the condenser layers of the bushing, and resulted in bringing the insula-

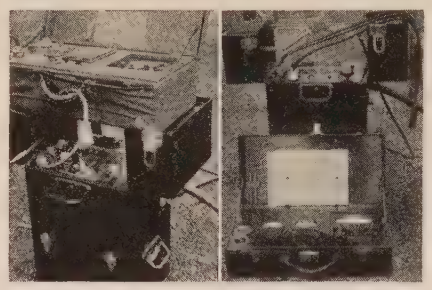


Fig. 5. Portable insulation tester as used in the field, complete with transformer control panel, and instrument case

Table I—Summary of Power-Factor Tests on Oil Circuit Breaker Bushings, 1929

Bushings tested	3,881
Faults found	122 (3.15%)
Bushing faults	58 (1.50%)
External faults	64 (1.65%)

Table II—Special Power-Factor Field Tests, June 1931, on 44-Kv Transformer Bushing Shown in Fig. 9

Test condition	% P. F.	Watts
Bushing in transformer tank (as found)	7.6	1.21
Bushing out of transformer tank	8.0	1.27
Bushing out—low end wiped	8.1	1.29
Bushing—top porcelain shell removed	7.5	1.13
Bushing 2—top porcelain shells removed	8.0	1.19
Bushing 3—top porcelain shells removed	8.2	1.24
Bushing 4—top porcelain shells removed	8.2	1.23
Felt washers between porcelain	36–98	0.21–1.45
Individual condensers (1 to 8)	6.9–15.0	1.07–6.7

Note: Felt washers between porcelain water-soaked insulation deteriorated.

Fig. 6. Testing a 33-kv potential transformer in the field with the portable insulation tester

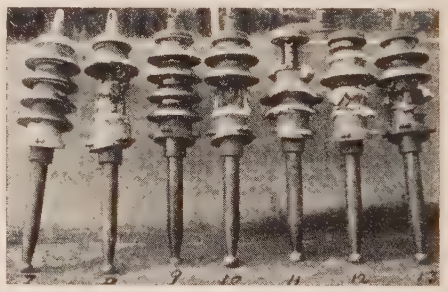


Fig. 7. Seven 44-kv bushings which failed during one lightning storm, June 1931

Table III—Power-Factor Tests in 1931 on 44-Kv Bushings

	Field Tests			Factory Tests			
Ref.	% P. F.	Watts	Megs.	% P. F.	60 Cy. Kv-F. O.	Impulse Kv (1 1/2 x 40)	Remarks
1	4.6	0.25	Inf.	6.43	190	400	O. K.[2]
2	6.2	0.31	Inf.	8.6	180	438	O. K.[2]
3	5.5	0.76	1,000	4.65	160[1]		Failed
4	5.8	0.45	1,000	3.75	175	410[1]	Failed
5	8.0	1.13	900	3.7	185[1]		Failed
6	9.5	1.93	Inf.		60[1]		Failed
7	10.5	1.42	500	3.55	190	350[1]	Failed

1. Bushing failed.
2. This bushing had bad insulation in outer condenser, but enough good insulation left to withstand puncture.

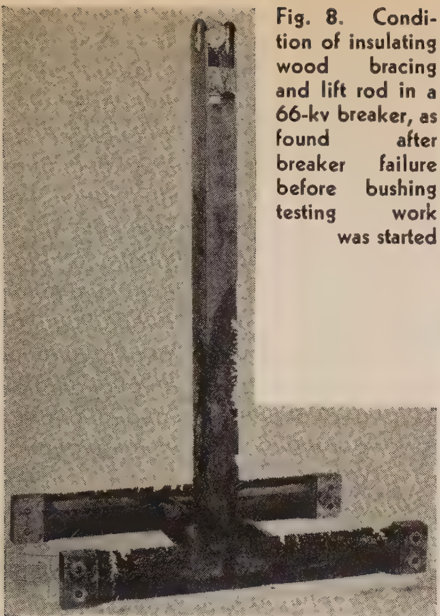


Fig. 8. Condition of insulating wood bracing and lift rod in a 66-kv breaker, as found after breaker failure before bushing testing work was started

Fig. 10. Field testing a 37-kv oil circuit breaker

Power-factor test set is located inside specially fitted light delivery truck

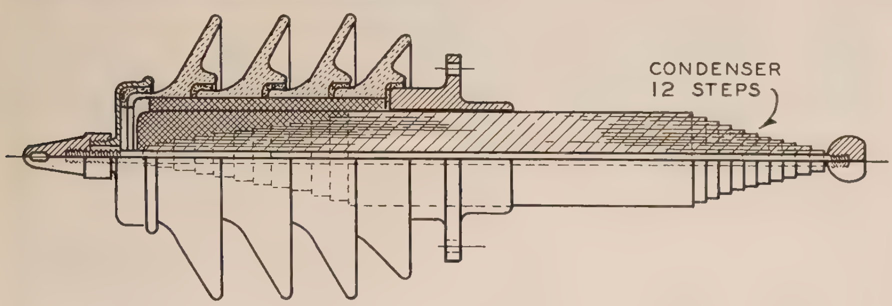


Fig. 9. A 44-kv bushing

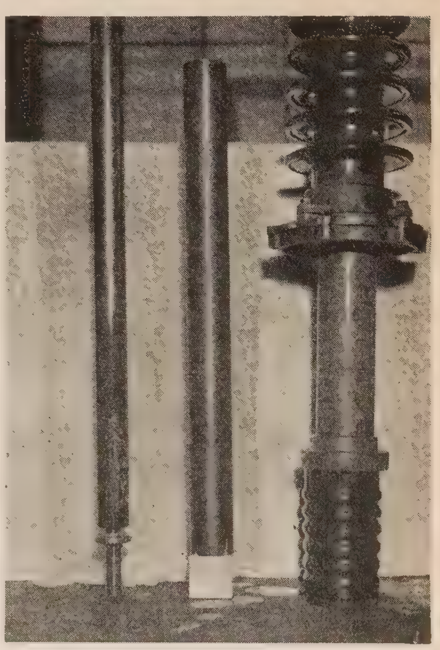


Fig. 11. 37-kv oil filled bushing found defective on field power-factor test

Note defective spots in insulation which broke down with 160 kv 60 cycles applied to bushing

Table IV—Analysis of Defective 37-Kv Oil Filled Bushing September 1932. (See Fig. 11)

	Per cent	Watts
Field test power factor	19.5	1.91
Test 24 hours after removal	42.0	....
Bushing oil (top)	17.1[1]	2.0
Stud insulation	46.0[2]	5.2
Insulating sleeve (top)	100.0[2]	5.8
Near bad spot in sleeve	95.0	11.0
Bushing after disassembling and filling with new oil	35.5	2.1
60-cycle test	broke down at 180 kv. Insulating sleeve punctured — creepage along stud insulation	

1. Oil Tested 19 kv.
2. Good insulation should be 2 to 3% approximately.

tion of some of them down to a point where they had a power factor as high as 0.15.

Some of the other early results that pointed to the absolute necessity of continuing power-factor testing can be gathered from Table III which shows the results of some power-factor tests made in 1931 on a group of 44-kv bushings. In this table there are shown both field and laboratory tests of 7 bushings, all of which had indicated defective condition by power factor tests in the field. On being found defective by field test, they were taken to the laboratory, power-factor tested by the laboratory test set, given 60-cycle flashover tests, and later, when they survived the 60-cycle test, given impulse tests with a $1^1/_2 \times 40$ wave. The interesting thing in connection with this table is that 5 of the 7 bushings failed on voltage test, and No. 4 and No. 7, although passing the 60-cycle test, both broke down under the impulse test. This, of course, is not in agreement with the expectation of the authors that a bushing which would meet the standard one-minute test, by which I presume is meant to be a 60-cycle test, would be expected to be a satisfactory bushing. Of course all of those who have gone into the problem of insulation coördination over the past 8 years or so, have found out a long time ago that a 60-cycle test is not adequate as a sole reliance of insulation strength.

The result of all of this work throughout 1929, and 1931, definitely led to the conclusion that:

(*a*). Periodic testing of bushings by power factor methods was essential in the present stage of the bushing art.

(*b*). That a satisfactory method and satisfactory instruments for carrying out such tests were available and could be relied upon to give consistent and reliable results. This does not check the authors' statements as to availability of equipment prior to the set they have described.

It might be interesting in this connection to show how our test equipment is being handled in the field. In Fig. 10 is shown a standard light $^1/_2$-ton truck with a delivery body, which is used by the test man to transport the test equipment to and in the field. In the rear of this truck all the necessary test equipment is carried, and is frequently used without removing the test transformer or instruments from the car. The equipment is shown at one of the substations with the test being carried out on a 37-kv breaker bushing. Note the simplicity of the arrangement and the fact that the test set has not been moved out of the car for obtaining the readings. The particular test equipment that we have used in the past 5 years is, of course, suitable for testing any type of bushing, and with proper application, to a great deal of insulation, some of which we have already started testing and on others of which we are feeling our way.

In Fig. 11 is shown a standard oil filled 37-kv bushing which, through the use of

Table V—Summary of Field Power Factor Tests on 8,376 Bushings (1932–33)

Type of Bushing	Oil Filled	Comp. Filled	Condenser	Solid Porc.	Totals & Per Cent
Bushings in service					
Number tested	4,210	2,344	936	146	7,636
"Defective"	270	218	124	27	639
"Remove"	247	106	74	17	444
% "defective"	6.4	9.3	13.2	18.5	8.4
% "remove"	5.9	4.5	7.9	11.6	5.8
Spare bushings					
Number tested	334	302	102	2	74.6
"Defective"	14	19	15[1]	0	48
"Remove"	11	10	43[1]	0	64
% "defective"	4.2	6.3	14.7[1]	0	6.5
% "remove"	3.3	3.3	42.1[1]	0	5.7

1. All rather old bushings stored in position in oil circuit breaker, in oil.

the test equipment, had the trouble definitely diagnosed. The history of this bushing is shown in Table IV. It will be noticed that this bushing was found on field test with a power factor of 0.195 and a watts loss of 1.91. The bushing was torn down and the insulation around the conductor was found to have a power factor of 0.46. The insulating sleeve had a power factor of approximately unity. The normal power factor of this insulation when tested separately should be in the order of 0.02 to 0.03. The bushing was then flushed out with clean oil and reassembled with the same insulating parts, and was found to have a power factor of 0.355 and a watts loss of 1.2. The 60-cycle test was then made on the bushing and the bushing broke down at 180 kv. The breakdown, which is clearly shown in Fig. 11, resulted in a puncture of the conductor and sleeve insulation. This is only one of a number of cases where bushings found defective on field tests, were actually investigated and the trouble definitely located.

In the past 5 years there have been tested on the American Gas and Electric Company system, some 15,000 bushings. A summary of the results found on over 50 per cent of these bushings is given in Table V. It will be noted that the percentage of defects which averaged 8.4 per cent, varied from 6.4 per cent to 18.5 per cent and the percentage which was recommended for removal averaging 5.8 per cent, varied from 4.5 per cent to 11.6 per cent. What is even more striking is that spare bushings, which are generally considered by the operator as his second line of defense, did not stand up a whole lot better. All of this goes to show that there is no such thing, apparently, as insulation, and particularly composite insulation subjected to exposure and action of the elements, that can be safely forgotten.

In closing, I think we ought to say that we know that as a result of our own work and the work of a number of other operating companies, power-factor bushing testing and general power-factor testing of insulation is no longer in the pioneer stage, and that it has a well established and solid background at the present time. In our own case, testing with the equipment described, reading watts loss and current, and calculating power factor has given most practical and excellent results.

We have found, too, that carrying on our tests entirely independently of the designers of the equipment has had its advantages, and that we have been able in doing that to set up perhaps more definite standards of safe and unsafe operating practice. Further information on the results obtained in our system has been given by Gross and Turner. (See "Testing Bushings and Insulation by Power-Factor Method," *Elec. World*, v. 103, 1934, p. 68–72 and p. 110–6.)

Impulse Generator Circuit Formulas

Discussion of a paper by J. L. Thomason published in the January 1934 issue, p. 169–76, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

P. H. McAuley: The author has made a rather complete tabulation of impulse circuit formulas. He states that their primary value is to prove that cathode ray oscillograms actually record test-piece voltages. Unquestionably, it is gratifying to be able to justify mathematically, established laboratory practices and measuring equipment. But it is to be regretted that reliable circuit analyses do not precede the working out of these relations in the laboratory. If the calculations had kept pace with practice, our impulse testing literature would not have so many inaccuracies and disagreements.

The author has based most of his results on a generator capacity of 0.01250 μf. This is a practical value quite likely to be found at least up to the 2,000-kv class. In Fig. 3 of the paper it is shown that, for the conditions assumed, a smooth wave voltage of only 50 per cent of the rating of the generator can be obtained. About 3,000 ohms series resistance is required to damp out the oscillations. These oscillations, occurring with inadequate series resistance, have caused many errors in voltage values in the past, particularly where the sphere gap has been used for voltage measurement. The sphere gap measures the crest value of the oscillation which may be as much as 25 per cent higher than the equivalent smooth wave flashover voltage of the test piece.

Another conclusion that follows for the wide range of conditions which the author has assumed concerns the wave front. The minimum wave front shown, Fig. 8 of the paper, is 0.9 μsec. This is further evidence of the impracticability of a wave with a $^1/_2$ μsec front.

Heavy Surge Currents—Generation and Measurement

Discussion of a paper by P. L. Bellaschi published in the January 1934 issue, p. 86–94, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 481–2.

W. G. Roman: A high current surge generator similar to that described by P. L. Bellaschi has been used for several months in the impulse laboratory at East Pittsburgh. It has been found very valuable in the study of lightning arrester performance at high surge currents.

Surge currents and voltages are measured with a cathode ray oscillograph. When making combination surge and normal frequency, or power follow tests, the surge generator can be synchronized with either crest of the normal frequency voltage. A galvanometer type oscillograph and a ballistic wattmeter are used to measure the normal frequency power follow. The ballistic wattmeter is valuable in statistical studies or in routine arrester tests. The capacitor units are arranged in 2 banks of 10 units each and can be used all in parallel at 100 kv or as a 2-stage generator at 200 kv. The physical arrangement of the capacitors, discharge gap, and test cell is shown in Fig. 1.

The compact arrangement of the circuit, and the use of several parallel discharge paths where possible, has resulted in a low equivalent inductance for the circuit. Therefore, although the surge generator is physically small, the current output is high. The discharge is a damped sine wave, the period being 19 μsec. At a charging voltage of 92 kv the current reaches a crest of 125,000 amp the first half cycle. The oscillating current decays to half value in approximately 40 μsec.

A surge current shunt with a very low ratio of inductance to resistance was developed. A sketch of this shunt is shown in Fig. 2. The resistance elements are twisted resistance wires spaced around the circumference of the concentric brass tubes. One of the resistance elements is shown in the sketch. The resistance elements have a slight amount of inductance and at high frequencies a voltage component leading the current by 90 deg will be induced. By looping one of the leads to the current measuring cable back through holes in the concentric tubes, as shown in the sketch, a voltage lagging the current by 90 deg is induced. By making this loop the proper

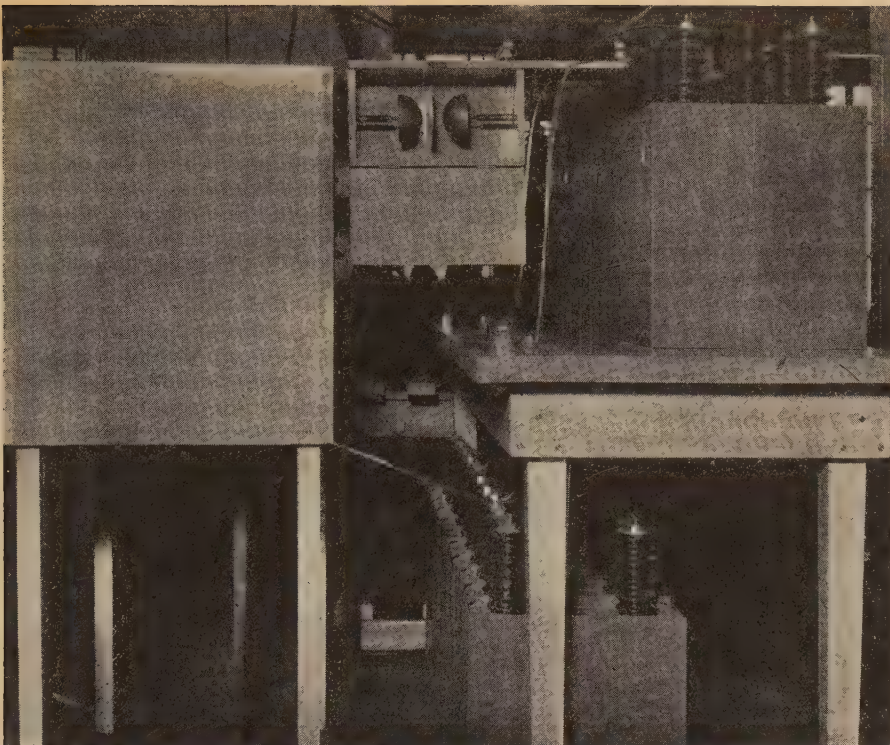


Fig. 1. High current surge generator showing capacitors, discharge gap, and test cell

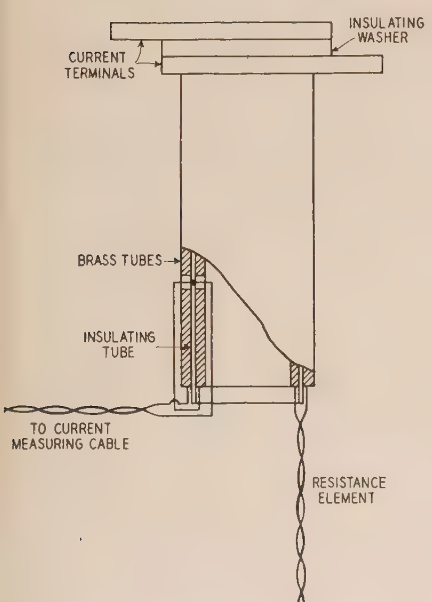


Fig. 2. Sketch of surge current shunt

size the leading and lagging components of voltage can be made to cancel and the shunt will have nearly a pure resistance characteristic. When thus compensated a typical shunt has a time constant of 0.07 μsec and the error at 100,000 cycles is less than 0.5 per cent.

P. L. Bellaschi: A review of the paper along with the interesting discussions which this paper has stimulated indicates clearly that the technique of heavy surge currents can now be considered well established for all practical purposes. The various points brought out in the discussions are either fully treated or summarized in the paper by specific as well as general statements, these statements being based on lengthy analysis and experiments that could not have been incorporated in minute detail in the paper without unduly lengthening the paper.

Theoretically speaking, there are various methods of securing a surge generator of low impedance. In fact a number of arrangements have been considered by the author, such as the fan-type arrangement of parallel condenser groups, the ring-type arrangement, etc. But, in addition to the ideal theoretical lay-out, other important practical considerations need be taken into account, such as for example: (1) The utilization of any apparatus already installed may be economically desirable; (2) the space requirements at the discharge gap is another consideration, particularly where the purpose of the test is to produce a direct-stroke current discharge to the fully assembled apparatus, excited and operating under conditions closely simulating service, and similar other practical considerations. It will be noted from Fig. 6 in the paper that the parallel condenser groups comprise substantially a fan-type arrangement. This arrangement meets the theoretical requirements of a heavy surge current generator, as well as the practical requirements in the way of physical space and facilities, required for conducting with full control and safety, tests on completely assembled apparatus, such as transformers with de-ion gap protection, fuse cutouts, lightning arresters, etc. The apparatus tested is enclosed in a steel tank (see Fig. 6) and is excited at normal operating voltage from a power source capable of supplying unusually heavy power current in the case of short circuit.

With the surge current generator described in the paper (see Fig. 6), the amplitude and duration of the currents attained (see Figs. 9 and 10) and used to test surge-proof distribution transformers with de-ion gap protection, simulate in severity the currents in the direct stroke of lightning. This surge current generator, as well as the one mentioned by Mr. Roman, may truly be considered *lightning current generators.* The surge currents that have been obtained and mentioned by Mr. Brownlee are more appropriately classified as of moderate severity.

The symmetrical aperiodic waves which are referred to by Mr. Brownlee may also be obtained with an autovalve block or element. The heavy surge current generator at Sharon is of sufficient capacity to generate and discharge through de-ion gaps unidirectional currents of durations as great as 40 μsec from crest to half-crest value (see oscillogram C, Fig. 10 of the paper).

The discussion presented by Mr. Brownlee on shunts is in accord with the analyses and experience of the writer. However, Mr. Brownlee has confined himself practically with the less difficult problem of low-current capacity shunts. The shunt B, Fig. 11 in the paper, is simple and rugged in construction, and is capable of measuring a surge current up to 150,000 to 200,000 amperes. This shunt can readily be replaced in case of damage and at a low cost. Calculated values of the resistance and inherent inductance for this type of shunt, given in Appendix II, if substituted in a numerical example will indicate that for all practical purposes this type of shunt is amply good; extensive experience confirms this. For slightly greater accuracy in reproducing the wave form of very fast waves, flat strips of thin ribbon separated by a few mils of insulation will give somewhat better results than the wire conductor, and for still more exact reproduction it is even desirable to compensate for the inherent inductive drop as mentioned by Mr. Roman (for illustration of compensated shunt, see "Generating 130,000 Amperes for Laboratory Testing," by P. L. Bellaschi and W. G. Roman, *Elec. J.*, March 1934, p. 96–100). These latter precautions become useful in extremely accurate or what may be termed scientific investigations, and also for waves much faster than are at present used.

The effects of skin and proximity effects were analyzed in sufficient detail by the writer and for conductors of high resistivity material these effects are of no practical importance. Similarly, the shunt capacity is of no importance.

Appendix III of the paper analyzes the physical problem of fusion of conductors and this analysis is well substantiated by experiments with actual surge currents. For further information on the laboratory investigations on heavy surge currents, Mr. Thomason is referred to the *Elec. J.*, issue of March 1934 and letters by the author published in *L'Elettrotecnica* during November 1933 and subsequently. The reference given by Mr. Thomason is of interest but no mathematical studies or analysis of the fusion characteristics of conductors are given therein. For some previous studies and analysis on this subject mention may be made to Reference (9), published as early as 1928.

As to the practical and fundamental knowledge of lightning currents, obtained in the laboratory, the extensive investiga-

tions on heavy surge currents described in the paper and correlation of these laboratory findings with field experience have now brought to practical realization a degree of protection of electrical apparatus against lightning which a few years ago was only to be hoped for. These laboratory investigations have also enhanced materially our fundamental knowledge of lightning phenomena observed in the field.

An A-C Potentiometer

Discussion of a paper by S. L. Burgwin published in the January 1934 issue, p. 108–13, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

C. L. Fortescue: Some 18 years ago there was considerable activity in the Institute in connection with potentiometer devices. Dr. Clayton Sharp at about that time wrote a paper in which he described various potentiometer methods for measuring the ratio and time lag of current transformers. I was particularly taken with the method using mutual inductance because it showed prospects of obtaining an absolute measuring device. Accordingly, I set out to build a potentiometer for the purpose of measuring the ratio and phase angle of current transformers using this scheme.

The instrument which I developed has been described (see "The Calibration of Current Transformers by Means of Mutual Inductances," by C. L. Fortescue, TRANS. A.I.E.E., v. 34, 1915, p. 1599–1615) and consisted of 2 main mutual inductances and auxiliary mutual inductances for fine adjustments. One of the mutual inductances had a current range of from 10 to 5,000 amp. All the mutual inductances were wound on toroidal marble coils, which had been accurately machined to within a few ten thousandths of an inch of the specified dimensions. However, in winding these toroids, which was done very carefully on a dividing machine, I overlooked one thing and that was the fact that in making a complete circuit with the solenoid around the toroid an extra turn is added at right angles to the other windings so that the mutual induction between this extra turn and the other windings passing through the toroid must be taken into account in the mutual induction. Consequently, when I came to check up the mutual induction of the coils, I found a small error from the calculated values which I could not account for as I had not taken into account this extra turn. As I recall, it was Dr. G. A. Campbell of the American Telephone and Telegraph Company who called my attention to this extra turn during the discussion of my paper.

The error due to this extra turn was exceedingly small and the mutual inductances were found to be almost perfectly astatic. Using this device, we were able to measure the ratio and phase angle of current transformers with great accuracy. We also used it experimentally to measure the resistance and reactance of reactors with a high degree of accuracy. In fact, the device was so delicate that a man passing within a few feet of the reactor and having a bunch of keys in his pockets would throw the instrument off zero. This device could also be used for measuring iron loss.

This device was designed principally to be used as an absolute standard for measuring ratio and phase angle of current transformers, and it has been used for this purpose and has given satisfaction during the past 18 years. The instrument used in connection with this device is a separately excited needle galvanometer so that the separate winding can be excited in phase and in quadrature by means of a phase transforming device. A remarkable thing about this potentiometer is that it is in continual use on our commercial testing floor at Sharon and has been found to be perfectly satisfactory and is unaffected by the regular commercial testing that is being carried on within a few feet of it.

I should like to point out also that the a-c calculating board is nothing more than a very large potentiometer in which 250 or more circuits are involved and by which the voltage and current distribution in these circuits can be measured accurately. The device for measuring voltage on the a-c board is a potentiometer device which gives in-phase and quadrature components of voltage. This a-c board has been in continual use for solving complicated network problems and has proved to be very satisfactory.

I. M. Stein: In the opening statement of his paper, Mr. Burgwin says "while the a-c potentiometer may not be adapted as well to a particular test as a more specialized meter or bridge circuit, its chief advantage is that it can be used satisfactorily for a very wide range of measurements." He then goes on to say "However, the use of the a-c potentiometer has been restricted greatly, probably because of several practical difficulties which never have been eliminated satisfactorily in spite of the many types of a-c potentiometers that have been developed."

The first quotation says in effect that the a-c potentiometer is a jack of all trades and a master of none. I think that that brief statement gives, as accurately as can be done in a brief statement, the real reason for the restricted use of the general purpose a-c potentiometer in this country.

To attribute the restricted use to slide wire difficulties is, I believe, definitely erroneous. Slide wires are very generally used in potentiometers having a limit of error in the order of 0.01 per cent, and I am confident that an actual count would show that there are more precise potentiometers of the slide wire type in successful general use than there are of all other types combined.

Mr. Burgwin refers to a paper by Thomas Spooner in the *Review of Scientific Instruments*. Spooner's paper refers to an a-c potentiometer of foreign manufacture and of recent design. It may be that in this recently designed instrument the slide wire construction was faulty.

The paper gives no statement of the accuracy attainable with the instrument described. I think that a summation of the various limits of error involved is an essential part of the description of any measuring instrument. On the other hand, the author refers several times to the use of his instrument in iron testing. In such measurements, a limit of error in the order of 1 per cent is customary because of the variation in individual samples of iron. Perhaps the author has no intention of claiming for his instrument the degree of accuracy usually associated with a potentiometer.

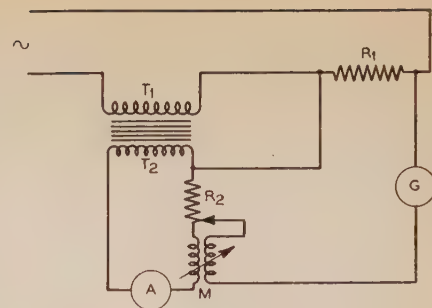


Fig. 1. A potentiometer circuit for the precise determination of ratios and phase angles of current transformers

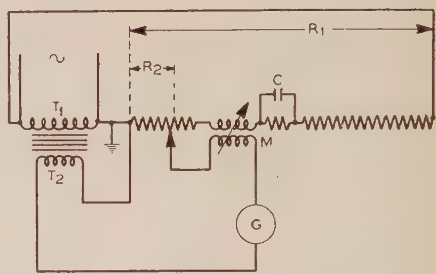


Fig. 2. A potentiometer circuit for the precise determination of ratios and phase angles of potential transformers

I wish to call attention to one source of error not even considered in the paper, that is, variation of temperature. For instance, in Appendix I it is shown that the quadrature relation between the 2 elements of the potentiometer depends on the sum of the resistances R_1, R_2, R_3, and R_4, some of which presumably are copper windings.

In contrast with general purpose a-c potentiometers, special purpose a-c measuring circuits, incorporating some of the important features of the potentiometer, are used extensively in this country. These are capable of the same order of accuracy as precise d-c potentiometers and, in general, are quite simple. Moreover, they all make use of a more or less standardized group of precise a-c measuring units so that having available a reasonably complete group of such units nearly any of the special purpose potentiometer circuits may be set up.

Figure 1 shows such a special-purpose circuit for the precise determinations of the ratio and phase angle of current transformers. This circuit has been in use for many years at the U.S. Bureau of Standards and in many other laboratories in this country. Figure 2 is a similar circuit for testing potential transformers.

Figure 3*a* shows a very simple special-purpose potentiometer circuit for core loss and permeability tests of iron cores. It will be seen that this circuit is similar to Fig. 6 in the paper, but that most of the apparatus in the a-c potentiometer has been eliminated. Measurements made in accordance

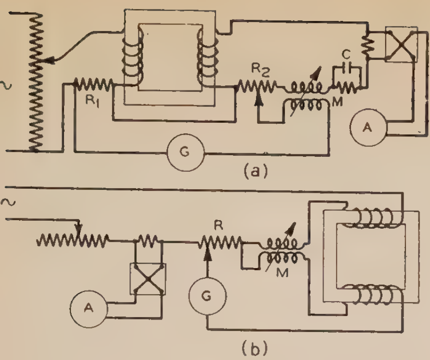


Fig. 3. Simple potentiometer circuits for core loss and permeability tests on iron cores

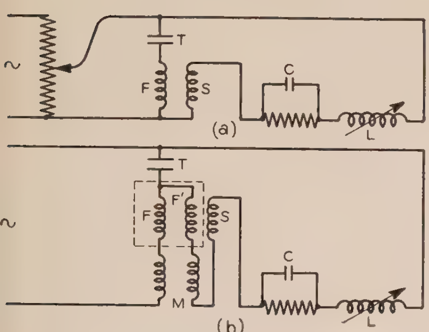


Fig. 4. A simple zero-deflection method for making the measurements indicated in Fig. 7 of the Burgwin paper

with Fig. 3*a* are more direct and therefore ess subject to error. The Fig. 3*a* arrangement was selected not because it is best for he purpose, but because it is similar to, out much simpler than, the arrangement hown in the paper. The Fig. 3*a* arrangement may be improved and simplified furher by transferring the ammeter and the orimary of the mutual inductance to the xciting circuit, by eliminating resistance R_2 and compensating unit C and then conecting the secondary winding of the test pecimen, the secondary of the mutual inluctance and the galvanometer all in series nd across a portion of resistance R_1; this rrangement is shown in Fig. 3*b*.

Figure 4 (upper) shows a very simple ero deflection method (although not a null nethod) for making the measurements indiated in Fig. 7 of the paper. This is generlly known as the "phase-defect" method. Only 2 units are required, the astatic dyamometer and a variable standard of selfnductance. The scale of the latter may be alibrated to read directly either phaseefect angle or power-factor.

The circuit of Fig 4 (upper) and also the ircuit of Fig. 7 in the paper result in some rror because of the losses in the coil in series rith the condenser being measured. By dding a compensating winding F', a small xed compensating mutual inductance M nd changing one potential connection, all s shown in Fig. 4 (lower), this error may e eliminated when using the Fig. 14 circuit.

May I conclude with a statement which iffers somewhat from Mr. Burgwin's openig statement. That is, while potentiomter principles may be well adapted to recise special-purpose a-c measuring circuits, the general purpose a-c potentiometer is a relatively inflexible high-cost investment and is not capable of the accuracy and convenience of operation usually associated with the name "potentiometer."

A New Demand Meter

Discussion of a paper by B. H. Smith published in the January 1934 issue, p. 94–5, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

P. M. Lincoln: The paper by B. H. Smith describing "A New Demand Meter" is a very interesting one. Not the least interesting feature of this paper is the evidence given therein of the recognition on the part of the Westinghouse engineering department that a demand meter which responds to the loads imposed thereon in accordance with an exponential law is a suitable one for any demand meter.

As Mr. Smith so clearly points out in his paper, the device which he describes has exactly the same law of response as does the thermal wattmeter, i. e., the exponential law. This raises the broad question as to the relative merits of demand meters having an exponential law of response compared to other devices that have been used in the past for measuring demand. It is to this question that I wish to confine my remarks, and particularly to compare the thermal wattmeter with other types.

The so-called "block interval" type of demand meter has been used from the very beginning of the measurement of demand, and has been accepted in the United States as the standard method of measuring demands. There are certain loading conditions for which the thermal meter and the block interval meter do not give the same indications, and it has been tacitly assumed in the past, particularly among United States meter users, that under these conditions it is the block interval type of meter that gives the correct results while the thermal type is in error. Searching analysis does not support this tacit assumption. Although this matter has been briefly discussed before (see "The Character of the Thermal Storage Demand Meter," TRANS. A.I.E.E., v. 37, 1918, p. 189–210) it may be well to point out again that where the loading conditions are such as to cause a difference in the indications of the 2 types, it is the thermal type and not the block interval type that gives the dependable indication.

In Fig. 1 is shown the relative indications of the block interval and the thermal types of demand meters. So long as the load is steady or the blocks of load drawn are of relatively long duration, the 2 types indicate the same value. As the blocks of load decrease in time of duration, the 2 types begin to differ and the shorter the time of load duration, the greater will be this difference. With a block of load lasting exactly 2-meter periods, the thermal type is exactly one per cent low compared to the block interval. As the block of load drawn becomes shorter than 2-meter periods, the difference in indication becomes greater. Also, the indication of the block interval type begins to become indefinite; this, as is well known, is because the block interval meter may "split the peak," that is, the whole of the block of load may occur within a single meter period or only a part of it. On the other hand, the indication of the thermal wattmeter is perfectly definite. As a given block of energy decreases in time and correspondingly increases in watts, the thermal meter continues to recognize the increased heating effect of these higher loads for shorter durations while the block interval meter does not. There is a very definite and accurate mathematical expression for the indication of a thermal meter when there is applied to it any given amount of energy (kilowatt-hours) during any given time. This expression is:

$$\text{Thermal meter indication} = \frac{\text{watts-minutes}}{t}\left(1 - e^{\frac{-2.302t}{t_1}}\right)$$

where

e = base of Napierian logarithmus
t_1 = time in minutes for thermal meter to reach 90 per cent of final
t = time in minutes of load duration

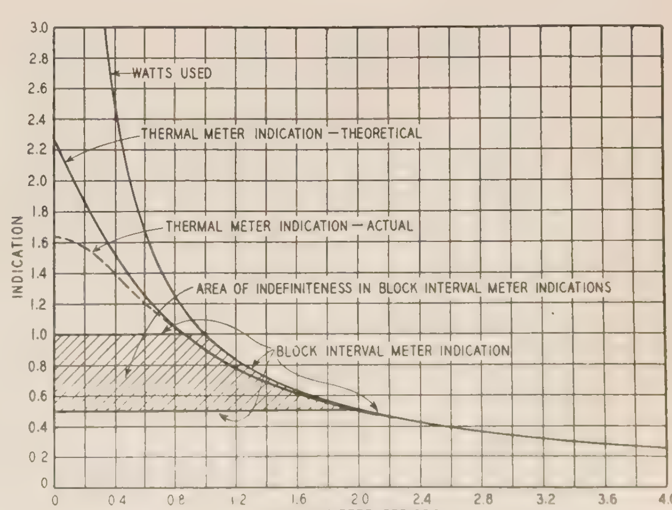


Fig. 1. Positive indications of block interval and thermal type demand meters when an isolated block of a given amount of energy (kilowatt hours) is applied during time intervals varying from zero to 4 times the time period of the block interval meter

From this expression it is readily seen that as t approaches zero and therefore the watts drawn approach infinity, the indication of the thermal wattmeter approaches a value that is 2,302 times the maximum indication of the block interval meter or 4,604 times its minimum indication. In Fig. 1 is shown the relative indications of the 2 types for all load duration intervals from zero to 4 times the time period of the block interval meter. The higher indication of the thermal type of meter for short load durations is quite defensible since it is obvious that a user of electric service who takes for instance his entire 15-min supply of energy in, say, so short a time as one minute, should pay more for taking his service in that abnormal manner than another user who spreads the same block of load over a longer period of time.

To express in words the relative characteristics of the thermal and block interval types of demand meters shown in Fig. 1, it may be said that the thermal meter recognizes in a consistent and accurate manner the "demand principle" for blocks of load of *all* time durations from zero to infinity. The block interval meter recognizes the "demand principle" reasonably accurately for load durations in excess of 2-meter periods, inaccurately to a high degree for load durations from one meter period to 2, and not at all for load durations of less than one meter period. The term "demand principle" may be defined as the effect of the loads drawn upon the heating of the equipment used to supply that load.

In Fig. 2 is shown another comparison between the thermal and block interval types of demand meters. This is essentially the same as Fig. 1. In Fig. 1, a given block of *energy* is assumed to be applied to each type during time intervals ranging from zero to 4 times the time period of the block interval meter. In Fig. 2, a given value of *watts* is assumed. The mathmatical expression for the indication of the thermal meter under the conditions of Fig. 2 is

$$\text{Thermal meter indication} = \left(1 - e\,2.302\,\frac{t}{t_1}\right)$$

$$= \left(1 - 10^{-\frac{t}{t_1}}\right) = \left(1 - \frac{1}{\text{anti}\log_{10}\frac{t}{t_1}}\right)$$

where

t_1 = time in minutes for thermal meter to reach 90 per cent of final or the time period of the block interval meter

t = time in minutes of load application

It will be noted that the mathematical expression for the thermal meter response in Fig. 2 is the same as the parenthetical part of that in Fig. 1.

An analysis of Figs. 1 and 2 can lead to only one conclusion, viz., that the fundamental principle underlying the block interval meter is unsound. For load durations of less than 2 meter periods, its indication is a matter of chance; its indication depends upon the instant that the meter happens to reset. Fortunately, most loads have a time of duration during maximum of more than 2 meter periods, so that in general the block interval meter gives an acceptable measure of demand. But there are exceptions to this general rule. Any device which is used to determine the amount which a user of electric service should pay for that service should, like Caesar's wife, be above suspicion in *every* case, not simply in the majority of cases. That the block interval meter is indefinite and inaccurate, at least on some loads, may easily be demonstrated by installing 2 on the same load, so adjusted that their time periods "break joints," that is, so that the time period of each overlaps the other by one-half. On some loads, 2 block interval meters so installed will show a very considerable difference in indication. Which of these 2 is the correct indication? The answer is neither.

The wide use and general acceptance of the block interval meter during the past 25 years or more do not alter the fact that its underlying principle is unsound. Up to 1917 it was the only available method of measuring demand and under these circumstances its use was quite justified. With the advent of demand measuring devices having an accurate principle of operation, there is no longer any excuse for continuing in use a device with an inaccurate principle of operation.

Why, may I ask, is it necessary to use the complicated mechanism described by Mr. Smith when the thermal meter is available? In this connection it is only proper to point out that the thermal demand meter is now in almost universal use in Canada, having been introduced there in 1918, and is in rapidly increasing use in the United States, having been introduced into the United States in 1928. The simplicity of the thermal meter is in marked contrast to the complexity of the device that Smith is now proposing.

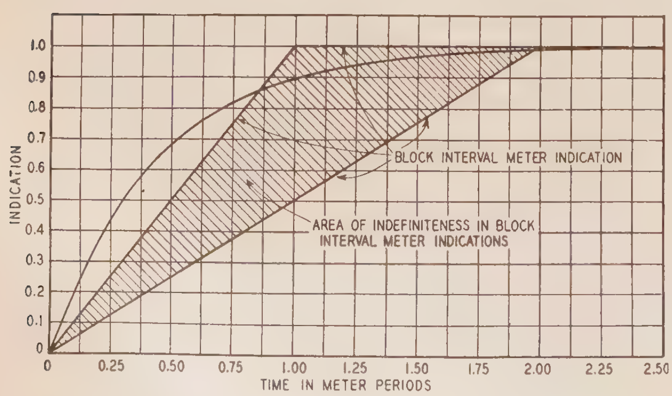


Fig. 2. Relative indications of block interval and thermal demand watt-meters when a given isolated load is applied during time intervals from zero to 2.5 times the time period of the block interval meter

R. E. Hellmund: With reference to Professor Lincoln's remarks, I recall several occasions when I discussed with the meter engineers of the Westinghouse Company the relative merits of the thermal demand principle proposed by Professor Lincoln and the "block interval" principle; some of these discussions dated as far back as twelve or thirteen years. On none of these occasions did any of the meter engineers fail to appreciate fully that, from a purely theoretical point of view, there was a great deal of merit in the Lincoln meter. The only reason why the "block interval" principle was considered more favorable for commercial work at that time was that it was simpler and more readily understood, a factor which is of great importance in handling meter problems because in this work we are by no means concerned with the engineering profession alone, but with various rate-making commissions and with the public at large as well. The manufacturer is after all obliged to produce those devices which find the greatest public acceptance, irrespective of what his own engineers may prefer from a theoretical point of view, and it was considerations of this nature and not a lack of understanding or appreciation of the principles propounded by Professor Lincoln which in general favored the development of the block interval demand meter in comparison with the thermal demand meter.

While the principles advocated by Professor Lincoln have naturally found some market acceptance in the past, only experience will show to what extent their acceptance can be increased, and only time will tell which of the 2 principles will find the most general acceptance. The users and customers, and not the manufacturers, will be the final judges in this matter.

B. H. Smith: I agree with Mr. Lincoln that it probably will be 15 years before this matter is settled to the satisfaction of all concerned. But 15 years is not a long time. The earth is said to be one hundred million years old or more. I can remember 15 or even 30 years ago—and it seems but yesterday.

As to the mechanical mechanism, the Westinghouse company has a very large number of kva meters in service with a ball mechanism which is very similar to the mechanism in the new demand meter. In this demand meters there is still a synchronous motor, always a difficult problem in former demand meter; but with the new mechanism there is practically no load on the motor and, consequently, the problem is much easier and I believe we have it solved.

Here, in my hand, is the complete demand attachment. It fits into existing watthour meters and thus avoids the installation expense of a separate demand meter. This expense with present thermal meters is one of the reasons why they have not been more extensively used. As I told Mr. Lincoln some time ago, he should design his thermal meter to go into existing watthour meters as an attachment.

News

Of Institute and Related Activities

North Eastern District to Meet at Worcester

THE TENTH annual meeting of the North Eastern District of the American Institute of Electrical Engineers will be held at Worcester, Mass., from Wednesday, May 16, to Friday, May 18, 1934. On Friday the meeting will be combined with the District Student Branch Convention.

Headquarters will be at the Bancroft Hotel, corner of Franklin and Portland Streets. This is one of the most comfortable hotels in Massachusetts with most adequate facilities for meetings of this character. The service is excellent, and the prices extremely reasonable. Special arrangements have been made with the management to provide rooms for the students on a dormitory plan at $1 per day.

The City of Worcester

Worcester is located in the heart of the Commonwealth of Massachusetts. It is a city of 200,000 population, the third largest in New England, centrally located for industry and commerce. It is connected by rail and super-highways to the principal markets of the Atlantic seaboard.

Its industry is diversified covering over 500 different items of manufactured articles. Included in this long list are: American Steel and Wire Company, manufacturers of wire and cables; M. J. Whittall Associates, rugs and carpets; Norton Company, grinding wheels and machinery; Crompton and Knowles Loom Works, textile machinery; Heald Machine Company, automatic machines and tools; Leland-Gifford Company, crank shafts and forging; the Royal Worcester Corset Company; and the United States Envelope, all internationally known.

Historically, Worcester is rich in interest. Twice, once in 1654 and again in 1683, the settlement was abandoned after the inhabitants sustained savage attacks by the Indians which reduced their numbers and destroyed their homes and crops. It was not until 1713 that a permanent settlement was established. From Worcester went forth General Artemas Ward, the first American to receive the commission of General under American authority; Colonel Timothy Bigelow, commander of the "Minute Men"; Isaiah Thomas in whose publication *The Massachusetts Spy* was printed the first copy of the Declaration of Independence to appear in a New England paper; General Rufus Putnam, Eli Whitney, George Bancroft, Elias Howe, Clara Barton, Edward Everett Hale, and a long list of names known to every child in the nation. The whole of New England abounds in historic shrines and natural beauty spots, all within an easy automobile ride of Worcester.

Worcester and the surrounding territory is served by the high voltage lines of the New England Power Company with local distribution made by companies operating under the New England Power Engineering and Service Corporation.

Wednesday's Activities

A most interesting program has been mapped out for the meeting. Immediately following the address of welcome by Vice-President J. Allen Johnson at 9:30 a.m. on Wednesday morning, 4 technical papers will be presented. After recess for luncheon another group of technical papers will be read and discussed. No special arrangements are being made for dinner on the first day of the meeting so that members may be free to look up acquaintances and dine with them. The evening entertainment will start at 8 p.m. and will consist of moving pictures with other feature entertainment.

Thursday's Activities

On Thursday morning 3 most interesting papers of a non-technical or a semi-technical character will be presented. This session is made short in order to provide sufficient time for the meeting of the District executive committee during the luncheon period. The afternoon will be given over to an inspection trip at the South Works of the American Steel & Wire Company. A most interesting visit is assured. In the evening a buffet lunch will replace the usual dinner. This will be followed by an informal dance and get-acquainted period.

Friday's Activities

The morning session on Friday will feature the student convention, as usual. This

The building on the left is the Bancroft Hotel on the corner of Franklin and Portland Streets, Worcester, Mass., which will be the headquarters for the Institute's North Eastern District meeting May 16–18, 1934. On the right is the Worcester Telegram-Gazette Building, and in the middle the Chamber of Commerce Building

will be under the direction of Prof. L. W. Hitchcock of the University of New Hampshire, who is chairman of the Branch counselor committee.

The scene of activities of the day will be transferred from the Hotel Bancroft to the campus of the Worcester Polytechnic Institute. Plans in addition to presentation of student technical papers in the morning include a trip to the Millbury dispatching station of the New England Power Company in the afternoon.

Annual Dinner

The annual dinner and presentation of prizes will be held at the Sanford Riley Dormitory of Worcester Polytechnic Institute at 6:30 p.m. on Friday. Following dinner both the student and senior sections will meet in the lecture room of the engineering laboratories where Dr. Robert J. Van De Graaff will give an illustrated lecture on "High Voltage and Its Application to Atomic Disintegration." If time permits, following Dr. Van De Graaff's lecture the local Student Branch will carry out some interesting experimental demonstrations of electrical apparatus.

Student Conference

After the morning session, the annual luncheon conference of the Branch chairmen and counselors will be held at the Sanford Riley Dormitory.

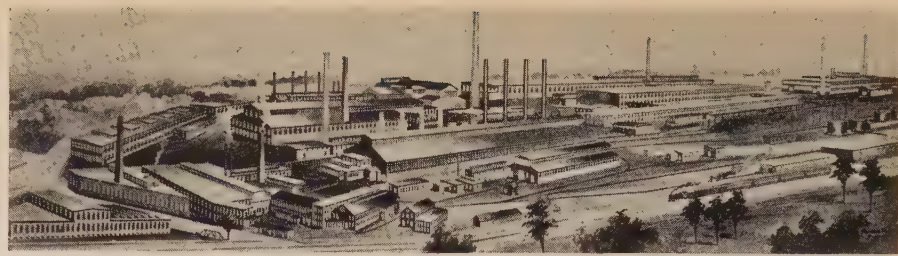
Saturday's Activities

For those who can stay over on Saturday arrangements have been made for a visit to the substation of the New England Power Company at Tewksbury, Mass. This is a 220-kv station, and will be of considerable interest to both the senior and student members.

Inspection Trips

Worcester is particularly rich in features for entertainment of members and guests. In addition to the plant of the American Steel & Wire Company, Worcester is the home of the Norton Company, manufacturer of abrasive materials, grinding wheels, tools, etc., the Heald Machine Company, manufacturer of precision tools and automatic machinery, and the Worcester Pressed Steel Company, manufacturer of pressed metal pieces as the name implies. Those wishing to do so may arrange for visits to any one or all 3 of these plants. The John W. Higgins Armory at the Worcester Pressed Steel Company will be of special interest. This is one of the most famous collections in the United States of armor from medieval time to the last of the armored knights. John W. Higgins, president of the Worcester Pressed Steel Company is an ardent student of arts in metals and has secured for his museum an elaborate collection depicting artistry in metal work from the 4 corners of the world.

In addition to these features of interest to the engineers in Worcester is found the internationally famous Worcester Antiquarian Society, a historical society of great interest to lovers of New England and an art museum exhibiting some of the world's famous masterpieces in painting and sculpture. As previously stated opportunity will be given to visit all of these points of interest.



South Works of the American Steel and Wire Company, Worcester, Mass., to which an inspection trip is scheduled on Thursday afternoon of the Institute's North Eastern District meeting to be held in Worcester May 16–18, 1934

Table I—Hotel Rates

Hotels	Single Room Running Water	Single Room With Bath	Double Room Running Water	Double Room With Bath
Bancroft*	$2.00	$2.50, 3.00, 3.50	$4.00	$4.50, 5.00
Aurora	$1.75, 2.00	$2.50, 3.00	$3.00, 3.50	$4.00, 5.00
Worcester	$1.75, 2.00	$2.50, 3.00	$3.00, 3.50	$4.00, 5.00

* Headquarters. Special rates for Students only—4 or more in room, individual cot beds, with bath, $1 per person

Women's Entertainment

A special women's committee has prepared a fine program for the entertainment of women visitors. On Wednesday afternoon a visit will be made to the Worcester Antiquarian Society and the Worcester Art Museum. A luncheon or tea at the John W. Higgins Armory, followed by bridge for those who desire, is planned for Thursday afternoon. On Friday there will be a luncheon at the Worcester Country Club with an opportunity to play bridge, tennis, or golf as desired.

Sports

Sports tournaments have not been scheduled but the committee will be glad to make arrangements for golf and tennis at any of the local clubs during the meeting.

Registration and Hotel Reservations

All planning to attend this meeting should register in advance, if possible, by writing to L. S. Leavitt, 11 Foster St., Worcester, Mass. Members should complete their registrations after arrival so as not to miss the opening session. There will be no registration fees.

Hotel reservations should be made directly with the hotel preferred. Rates for the headquarters hotel, Hotel Bancroft, the Aurora Hotel, and the Worcester Hotel are given in Table I. Both of the last 2 named hotels are under the same management.

An information desk will be open all day Wednesday and Thursday and during the morning of Friday for the convenience of members.

Parking

Ample parking space will be found in the vicinity of the Bancroft Hotel. Special arrangements have been made whereby A.I.E.E. members, and visitors, will be able to park their cars in the Bancroft Garage, 24 Portland Street (just around the corner from the hotel) at $0.75 per day. This includes the privilege of taking the car out as often as desired without additional charge. Open air parking space on Federal Street at the rear of the hotel also is available at a small fee.

Program

Most of the technical papers to be presented for discussion at the meeting have been published in this and preceding issues of Electrical Engineering. For those papers which have been published, reference to the issue and page is given with the title in the following program. Members who wish to follow the presentation in detail and discuss the papers are urged to take the necessary issues to the meeting with them.

Because it is contemplated that the May 1934 issue of Electrical Engineering will be devoted to the fiftieth anniversary of the A.I.E.E., those papers which have not been made available in time for inclusion in the April issue will not be published in advance. For this latter group, arrangements are being made with the authors to supply mimeographed copies.

All technical sessions, with the exception of those scheduled on Friday, will be held at the Bancroft Hotel. The sessions on Friday will be held in the lecture rooms of the Worcester Polytechnic Institute.

Wednesday, May 16

9:00 a.m.—Registration

9:30 a.m.—Opening Session

Opening Address, J. Allen Johnson, vice-president, North Eastern District, A.I.E.E.

Selected Subjects—T. A. Worcester, *chairman*

A New Type of Warble Tone Oscillator, W. H. Bliss, University of Maine. April, p. 547–50

A Vacuum Tube Controlled Rectifier, C. B. Foos, General Electric Co. April, p. 568–70

Thyratron Tube Control of High Speed Resistance Welders, W. C. Hutchins and O. W. Livingston, General Electric Co. Not published

The M.I.T. Power-Factor Bridge and Associated Oil Cell, and the Power-Factor Measurement of Small Oil Samples, J. C. Balsbaugh, N. D. Kenney, and Alfred Herzenberg, Massachusetts Institute of Technology. Not published

Future AIEE Meetings

North Eastern District meeting,
Worcester, Mass., May 16–18, 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept. 3–7, 1934

2:00 p.m.—Transmission and Distribution, I. E. Moultrop, *chairman*

SHUNT RESISTORS FOR REACTORS—II, F. H. Kierstead and L. V. Bewley, General Electric Co. March, p. 411–8

THEORY OF PRIMARY NETWORKS—PART II, F. M. Starr, General Electric Co. March, p. 426–31

DOUBLE UNBALANCES IN 3-PHASE NETWORKS AND THEIR SOLUTION ON THE A-C CALCULATING BOARD, E. W. Kimbark Not published

EXPERIMENTS IN FATAL ELECTRIC SHOCK, A. G. Conrad and H. W. Haggard, Yale University. March, p. 399-402

8:00 p.m.—Special Entertainment Feature

Thursday, May 17

9:00 a.m.—General Session, Louis S. Leavitt, *chairman*

FIFTY YEARS OF THE A.I.E.E., by C. F. Scott, Yale University.

THE INSIDE WORKINGS OF THE A.I.E.E., J. Allen Johnson, vice-president, North Eastern District, A.I.E.E.

SPEED CONTROL PROBLEMS OF INTERCONNECTED OPERATION, Robert Brandt, New England Power Engineering and Service Corp.

12:00 noon—District Executive Committee Luncheon

1:30 p.m.—Assemble for transportation to South Works, American Steel and Wire Co.

2:00 p.m.—Inspection trip through South Works of the American Steel and Wire Co.

6:30 p.m.—Buffet luncheon followed by informal dancing

Friday, May 18

9:00 a.m.—Student Technical Session, Professor L. W. Hitchcock, chairman Student counselors' committee

Meeting held at Electrical Engineering Laboratory, Worcester Polytechnic Institute, corner of West and Salisbury Streets

12:00 noon—Luncheon Conference of Counselors and Branch Chairmen

2:00 p.m.—Student Inspection Trips

2:00 p.m.—Electrical Machinery, C. A. M. Weber, *chairman*

IRREGULAR WINDINGS IN WOUND ROTOR INDUCTION MOTORS, R. E. Hellmund and C. G. Veinott, Westinghouse Electric and Mfg. Co. Feb., p. 342–6

STRAY LOAD LOSS TEST ON INDUCTION MACHINES, T. H. Morgan, Worcester Polytechnic Institute, and P. M. Narbutovskih, Graduate Student, Stanford University. Feb., p. 286–90

SOME PROBLEMS INVOLVING ADJUSTED SYNCHRONOUS REACTANCE, H. B. Dwight, Massachusetts Institute of Technology. April, p. 566–8

TRANSFORMER REACTANCE AND LOSSES WITH NONUNIFORM WINDINGS, H. O. Stephens, General Electric Co. Feb., p. 346–9

6:30 p.m.—Dinner at Sanford Riley Dormitory, Worcester Polytechnic Institute

8:00 p.m.—Illustrated lecture—HIGH VOLTAGE AND ITS APPLICATION TO ATOMIC DISINTEGRATION," by Dr. Robert J. Van De Graaff.

Saturday, May 19

The committee will be glad to make arrangements for a visit to the 220-kv substation of the New England Power Company at Tewksbury Mass., for any desiring to make this trip.

RULES ON PRESENTING AND DISCUSSING PAPERS

At the technical sessions, papers will be presented in abstract, 10 min being allowed for each paper unless otherwise arranged or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 min are allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication should be typewritten and submitted in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before June 1, 1934.

COMMITTEE

The District meeting committee in charge of this meeting consists of: J. Allen Johnson, *chairman*, vice-president, North Eastern District; A. C. Stevens, secretary-treasurer, North Eastern District; L. W. Hitchcock, chairman of Student Counselors, North Eastern District; and L. S. Leavitt, R. P. Bullen, W. H. Timbie, J. S. Henderson, B. K. Northrop, and W. B. Hall.

Floodlighting of this building in Worcester, Mass., the city selected for the Institute's North Eastern District meeting to be held May 16–18, 1934, makes possible the flying of the flag 24 hours a day. The building is the Soldier's Memorial on Lincoln Square

North Eastern District to Hold Student Convention

The student Branch convention for the Institute's North Eastern District is to be held on Friday, May 18, 1934, at Worcester, Mass., in conjunction with the tenth annual meeting of this District, as announced in an item appearing on preceding pages of the news section of this issue. The Bancroft Hotel is to be the headquarters for the District meeting on Wednesday and Thursday, but all activities scheduled for Friday and including those of Friday evening are to be at the Worcester Polytechnic Institute.

The Branch counselors are in a key position to insure the success of this annual Student activity by encouraging the presentation of Student papers and by arranging for Student attendance. Inspection trips can well be planned with Worcester as the objective either on Thursday, May

17, when a visit is already scheduled in the afternoon to the South Works of the American Steel and Wire Company, or Friday, May 18, for participation in the student technical session, and the usual afternoon trip to one of the industries. The banquet, heretofore held on Thursday evening, is planned for Friday evening. It is to be followed by an illustrated lecture "High Voltage and Its Applications to a Disintegration" by Dr. Robert J. Van De Graaff of Massachusetts Institute of Technology. A visit to the New England Power Company's station at Tewksbury is planned for Saturday.

L. W. Hitchcock (A'11) professor of electrical engineering, University of New Hampshire, Durham, is chairman of the Branch counselors committee.

A.I.E.E. Executive Committee Meets

A meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on March 9, 1934, in place of the regular meeting of the board of directors.

Present: John B. Whitehead, chairman; H. P. Charlesworth, J. Allen Johnson, Everett S. Lee, E. B. Meyer, and W. I. Slichter, members of the committee; A. E. Knowlton and L. W. W. Morrow, members of the board of directors; and H. H. Henline, national secretary.

Report of a meeting of the board of examiners held February 28, 1934, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken upon pending applications: 2 applicants were transferred to the grade of Fellow; 7 applicants were elected and 17 were transferred to the grade of Member; 47 applicants were elected to the grade of Associate; 153 students were enrolled.

The Finance committee reported expenditures for the month of February amounting to $18,181.74. Report approved.

Financial reports of the 1934 winter convention, held in New York, January 23–26, were presented, and the committee voted its appreciation of the effective arrangements made by the convention committee and of the successful financial outcome.

The dates, September 3–7, inclusive, were approved for the 1934 Pacific Coast Convention, in Salt Lake City, Utah.

Col. William B. Jackson was reappointed a representative of the Institute upon the Commission of Washington Award for the 2-year term beginning June 1, 1934.

Dr. John B. Whitehead was nominated for appointment as a member, representing the Institute, of the divison of engineering and industrial research, National Research Council, for the 3-year term beginning July 1, 1934, succeeding H. P. Charlesworth, whose term expires at that time and who is ineligible for immediate reappointment.

Approval was given to the appointment by the president of the following committee of tellers to canvass, count, and report upon the election ballots cast for Institute officers: W. E. Coover, chairman, J. T. Binford, A. Hagstad, Henry Kurz, W. C. Plumer, W. B. Snow, and H. B. Stoddard.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

To Institute Members Planning Trips Abroad

Members of the Institute who contemplate visiting foreign countries are reminded that since 1912 the Institute has had reciprocal arrangements with a number of foreign engineering societies for the exchange of visiting member privileges, which entitle members of the Institute while abroad to membership privileges in these societies for a period of 3 months and members of foreign societies visiting the United States to the privileges of Institute membership for a like period of time, upon presentation of proper credentials. A form of certificate which serves as credentials from the Institute to the foreign societies for the use of Institute members desiring to avail themselves of these exchange privileges may be obtained upon application to Institute headquarters, New York. The members should specify which country or countries they expect to visit, so that the proper number of certificates may be provided, one certificate being addressed to only one society.

The societies with which these reciprocal arrangements have been established and are still in effect are: Institution of Electrical Engineers (Great Britain), Société Française des Electriciens (France), Association Suisse des Electriciens (Switzerland), Associazione Elettrotecnica Italiana (Italy), Koninklijk Instituut van Ingenieurs (Holland), Verband Deutscher Elektrotechniker E. V. (Germany), Norsk Elektroteknisk Forening (Norway), Svenska Teknologforeningen (Sweden), Stowarzyszenie Elektrykow Polskich (Poland), Elektrotechnicky Svaz Ceskoslovensky (Czechoslovakia), The Institution of Engineers, Australia (Australia), Denki Gakkwai (Japan), and South African Institute of Electrical Engineers (South Africa).

Pacific Coast Convention Dates Selected

The dates of September 3–7, inclusive, have been approved by the Institute's executive committee for the 1934 Pacific Coast convention to be held in Salt Lake City, Utah. This convention takes the place of that originally scheduled to be held in Salt Lake City, September 4–8, 1933, but subsequently postponed.

The 1934 Pacific Coast convention committee has been appointed by President Whitehead, and plans are now actively progressing toward the arranging of a successful meeting.

It is planned that technical papers to be discussed at this convention will have been published in ELECTRICAL ENGINEERING in advance of the convention, in accordance with the Institute's newly adopted publication program. Details of the convention, including the technical program, entertainment features, and other events, will be given in future issues of ELECTRICAL ENGINEERING.

Tentative Plans for Summer Convention Are Announced

THE FIFTIETH annual summer convention of the A.I.E.E. will be held at Hot Springs, Va., June 25–29, 1934, with headquarters in the Homestead Hotel. This picturesque setting with its excellent facilities for sports and recreation together with a well-rounded technical program offers an ideal opportunity for members and their guests to enjoy a very pleasant and profitable week. As an additional feature this year, the opening session will be devoted partly to a special program commemorating the 50th Anniversary of the Institute, in which prominent members will take part.

The technical program which has been tentatively arranged calls for 7 sessions: education, insulators, power generation, automatic stations, electrical machinery, instruments and measurements, and communication. Technical papers for these several sessions will have been published in ELECTRICAL ENGINEERING so that any member interested will have ample opportunity to prepare thoughtful written discussion on any paper or papers of importance to him. The treatment of the subject of education will consider industry demands, present economic conditions, and the encouragement of initiative in the engineering student. Power generation will treat a hydroelectric survey of broad scope and the New York generating system as it aids network operation. The communication session is expected to present several papers dealing with the wide-band open-wire system of program transmission and shielding against inductive exposure. In addition other sessions will offer a number of papers which will outline some of the latest developments in theory, design, and the fabrication of electrical apparatus.

The general convention committee for the 1934 summer convention consists of the following members: W. S. Rodman, chairman; C. A. Robinson, vice-chairman; R. C. Bailey, secretary; E. P. Coles, R. N. Conwell, F. M. Craft, S. A. Flemister, J. T. Graff, E. L. Lockwood, W. R. McCann, and I. Melville Stein.

More complete information in regard to the program for the summer convention will be announced in subsequent issues of ELECTRICAL ENGINEERING. Arrange your plans now so as to be able to attend the annual summer convention at Hot Springs, Va.

Technical Committee Activities Proposed for Sections and Districts

This statement from I. Melville Stein, chairman of the A.I.E.E. Sections committee outlines a proposal that merits the thoughtful attention of every member of the Institute in order that the subject may be discussed thoroughly and constructively at the annual conference of officers, delegates, and members that will be an important part of the program of the fiftieth annual summer convention, to be held June 25–29, 1934, at Hot Springs, Va.

THREE of the most important activities of the American Institute of Electrical Engineers are: (1) its technical meetings, (2) its publications, and (3) the work of its technical committees.

It hardly can be questioned that the greatest mutual benefit to the membership and to the Institute as a whole comes with the participation in these activities by the maximum number of members. The function of the Institute is to provide the opportunity for such initiative on the part of individual members, and each member should take full advantage of the opportunities offered.

About a third of a century ago, it was realized that the Institute was not providing for its members remote from headquarters adequate opportunity to participate in technical meetings. Due largely to the foresight and efforts of Dr. Charles F. Scott, then president of the Institute, the idea of establishing Sections in many parts of the country, was given a great impetus. As a result, many Institute Sections were organized during and shortly following President Scott's term in office. The effect was quite remarkable. The membership of the Institute, which had been the smallest among the four Founder Societies increased abruptly until it became the largest. While an increase in Institute membership is in itself not a measure of success, it is an excellent index of the interest and participation in Institute activities, which are the real objectives.

Somewhat later, further opportunity for general participation in technical meetings of the Institute was offered by the formation of Districts and the provision for District Conventions.

Very recently, opportunity for all members to gain greater advantages from the Institute publications was established by the new publication policy, which provides for printing promptly and in full in ELECTRICAL ENGINEERING all papers and discussions accepted by the Institute.

Opportunity for Membership Participation

Up to the present time the opportunity for general participation in the third important activity of the Institute, namely, technical committee work, has not been provided. This, of course, is not intentional. On the contrary, the matter has been discussed many times over a considerable period of years, with the hope of finding a satisfactory plan which would provide for more general participation in the work of the technical committees. Always there appeared some important obstacle in the nature of something which would have made general participation by the membership a handicap rather than a help to the technical committees. Recently the study that has been devoted to this problem has brought forth a tentative plan which aims to provide for general participation in technical committee work in a way that should be a help rather than a handicap to the work of these committees.

As in the case of the technical meetings and publications of the Institute, the plan aims to provide full *opportunity* for general participation in technical committee activities, leaving it to each individual member to take the *initiative* in actually participating.

The proposed plan has been reviewed carefully by the technical program committee and by the committee on coördination of Institute activities. These 2 committees are in agreement that the plan should be presented for consideration by the delegates at the annual conference of officers, delegates, and members to be held during the forthcoming summer convention at Hot Springs, Virginia. It is the purpose of this article to give the proposed plan advance publicity, so that each member of the Institute may have the opportunity to discuss it with his Section delegate prior to the conference.

Details of Proposed Plan

Briefly, the tentative plan proposed is as follows:

1. Each Fellow, Member, and Associate of the Institute would be asked to communicate, to a duly appointed officer in his Section, his wishes with regard to becoming affiliated with one or more of the Institute's technical committees. There are 18 technical committees at present. Of course, no member would be under obligation to affiliate with any technical committee.

2. If in any Section there were a reasonable number of members, for instance 5, desiring to affiliate with a particular technical committee, the authorized Section officer would call a meeting of that group for the purpose of organizing that particular *Section Technical Committee*. The members so assembled would elect their own chairman. Thus in large Sections there probably would be set up as many Section technical committees as there are national technical committees. In smaller Sections, it is likely that the full number of technical committees would not be organized.

3. From among the elected Section chairmen of a particular technical committee in each District, there would be appointed a District chairman of that particular technical committee. Each District chairman so appointed automatically would become a member of the corresponding national technical committee. Probably each vice-president would appoint the District chairmen in his District.

4. Thus, included in each national technical committee, there would be 10 members, who, in the first instance, had been elected to serve as Section chairmen of that technical committee and then appointed to serve as District chairmen of the same committee. Also on each national technical committee, there would be at least an equal number of members appointed at large in the usual way.

The ways in which these Section technical committees could coöperate in the technical committee activities of the Institute are many, but space in which to enumerate them is not available here. Of course, those members who for some time have favored an expansion of the Institute's technical committee activities are well aware of the advantages to be gained.

Comments Wanted

In addition to discussing this plan with his Section delegate prior to the delegate's conference at the summer convention, June 25–29, it is suggested that any member wishing to comment on this proposed plan send his comments to I. Melville Stein, chairman of the A.I.E.E. sections committee, at 4901 Stenton Avenue, Philadelphia, Pa.

Southern District Holds Student Conference

The seventh annual student activity conference of the Southern District of the A.I.E.E. was held at North Carolina State College, Raleigh, January 11–13, 1934. About 200 students and faculty members, from 16 colleges, attended this conference. At the morning session, a group of student papers was presented. These were "Determination of Sequence Constants of a Synchronous Motor," by William E. Dean, Jr., student, University of Tennessee; "Electrically Tied Synchronous Motors," by C. W. Trieste, student, University of Florida; "The Selection and Application of Photoelectric Cells," by R. B. Shores, student, Clemson Agricultural College; "Mercury Vapor Process of Generating Power," by R. S. Wellons, student, Georgia School of Technology; "Public Utility Regulation in Southern States," by William L. Ridenhour, student, University of North Carolina; and "Kindling of Electric Impulse Sparkover," by A. J. McCullough, student, University of Alabama.

The afternoon meeting was called to order by Prof. R. S. Fouraker, as chairman, who appointed Joseph Weil as secretary. Prof. Claudius Lee was elected chairman of the eighth students activities conference to be held at Virginia Polytechnic Institute, Blacksburg, Va., in 1935. Professor Lee was also named as the delegate to represent the southern Branches of the Institute at the annual summer convention for 1934.

At the discussion of student activities during the afternoon the students themselves participated actively, notwithstanding the fact that there were many visitors and counselors present. Representatives from different Branches told of the projects that have been used by their Branches to

increase attendance at meetings. Plans were discussed which might be used most effectively for arousing and maintaining the interest of the students in the Institute.

Interest was shown concerning the question of vocational guidance. The value of guidance and examples of where this work has been beneficial were discussed.

A banquet was held Friday evening at which H. M. York, chairman of the North Carolina State College Branch, was toastmaster. During the banquet prizes for the winning student papers were announced and presented as follows:

First prize, $25 to R. B. Shores
Second prize, $10 to R. S. Wellons
Third prize, $5 to W. L. Ridenhour

Inspection trips were made on Saturday to Duke University at Durham, and to the University of North Carolina at Chapel Hill.

In addition to F. M. Craft, vice-president A.I.E.E., the following student counselors were in attendance:

W. W. Hill	Alabama Polytechnic Institute
F. R. Maxwell, Jr.	University of Alabama
S. R. Rhodes	Clemson Agricultural College
W. J. Seeley	Duke University
Joseph Weil	University of Florida
T. W. Fitzgerald	Georgia School of Technology
S. A. Bureau	University of Kentucky
J. M. Houchens	University of Louisville
L. H. Fox	Mississippi State College
R. S. Fouraker	North Carolina State College
William Hand Brown	North Carolina State College
W. J. Miller	University of North Carolina
R. F. Stainback	University of North Carolina
J. E. Lear	University of North Carolina
T. E. Ball	University of South Carolina
J. E. Tarboux	University of Tennessee
Claudius Lee	Virginia Polytechnic Institute
J. S. Miller, Jr.	University of Virginia

Electronic Show Conducted by Students

The meeting of the Institute's Student Branch at Pennsylvania State College, held February 21, 1934, was on the subject of vacuum tubes, and included an exhibit of vacuum tubes and an electronic show. The meeting also took on the nature of a celebration of the Institute's 50th anniversary, inasmuch as a brief ceremony at the beginning of the meeting was devoted to this purpose.

The papers and demonstrations were conducted by senior electrical engineers. A discussion of electron tubes entitled "The Electronic Age" by D. Robertson was given. Following this, the more important types of tubes were described and exhibited by F. C. Schwerer, and the fundamental principles of the construction and operation of the more common types were then given by W. C. Johnson. In the electronic show which followed, the demonstrations and the names of the students conducting these were:

1. Mobile Color Control	J. K. Walter
2. The Sensitron	D. T. Costa, W. E. Ferry and L. H. Wurster
3. Motor Speed Control	R. W. Barnitz and H. J. West
4. Futuristic Lighting Control	J. F. Giampiltro and D. M. Hutchinson
5. Electronic Eyes	R. C. Hollobaugh, M. J. Petscavage and F. W. Sell
6. Grid Glow Stroboscope	C. N. Bushey, D. S. Dietz and M. A. Sayland
7. Electronic Accordion	S. W. Smith, D. J. Troup, and P. S. Young
8. Electronic Bars	E. A. Bradford, J. N Fogg, and R. C. Schlaack
9. The Coloraudio	C. E. Disney, L. E. Fredrickson, and F. S. Miller
10. Sequence Control	E. Heath and E. V. Osterhout
11. The Vocalite	N. S. Young
12. Music Transmitted Over Light Beam	J. D. Colvin
13. Rotating Disks and Neon Glow Lamp	F. W. Sell

Engineering Foundation

Outline of Joint Engineering Organizations

A brief résumé of the organization and objects of United Engineering Trustees, Inc., and its 3 departments, namely, the administrative department, The Engineering Foundation, and the Engineering Societies Library, follows:

United Engineering Trustees, Inc., was organized in 1904 under the name of the United Engineering Society "to advance the engineering arts and sciences in all their branches, to further research in science and in engineering, to maintain a free public engineering library, and to advance in any other manner the profession of engineering and the good of mankind." It is now the joint agency of the 4 national societies representing the civil, mining and metallurgical, mechanical, and electrical engineers.

Administrative Department

United Engineering Trustees, Inc., as the agency of these 4 societies, owns and administers the Engineering Societies Building at 33 West 39th street, New York, N. Y., and the funds related thereto. It also administers the following trust funds: Engineering Foundation fund, library endowment fund, Henry R. Towne engineering fund, Edward Dean Adams fund, John Fritz Medal fund, and depreciation and renewal fund (for the Engineering Societies Building). Management of the building and all trust funds is in the hands of the administrative department of United Engineering Trustees, Inc., under the direction of its board of trustees.

The American societies of civil, mining and metallurgical, mechanical, and electrical engineers, through United Engineering Trustees, Inc., have equal interests in the ownership, occupancy, and administration of the building, which is run on a coöperative plan. The Engineering Societies Building houses also several other organizations in which engineers are interested.

The Engineering Foundation

The Engineering Foundation, founded by Ambrose Swasey (HM'28) is entrusted with the expenditure of the income of endowments and other funds "for the furtherance of research in science and engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." Its present preferred activity is engineering research. The Engineering Foundation coöperates with the 4 national engineering societies of which United Engineering Trustees, Inc., is the joint agency, with other organizations, and with individuals, in seeking additional knowledge through active, wisely directed research. It issues Research Narratives and other publications. It also has aided in establishing other research organizations.

Engineering Societies Library

The joint library of the national societies of civil, mining and metallurgical, mechanical, and electrical engineers is a free public library, which, with its numerous activities, is operated for users at a distance as well as for those who visit its rooms in the Engineering Societies Building. The library maintains a staff of technically trained searchers and translators, as well as reference assistants. It makes photoprints of any material in its collection and through a card service keeps subscribers informed of articles in periodicals on subjects in which they may be interested.

Election Held by Engineering Foundation

At its annual meeting February 15, 1934, the Engineering Foundation's board reelected as its chairman George W. Fuller, consulting engineer, former vice-president of the American Society of Civil Engineers, New York, N. Y., and a member of the firm of Fuller and McClintock. H. P. Charlesworth (M'22, F'28, and junior past-president) assistant chief engineer, American Telephone and Telegraph Company, New York, N. Y., was reëlected a vice-chairman. D. R. Yarnall was also elected a vice-chairman. These members, together with E. R. Fish and J. V. N. Dorr, constitute the executive committee. Dr. A. D. Flinn continues as secretary and director.

Members of The Engineering Foundation's board whose terms began at the annual meeting on February 15, 1934, and expire at the annual meeting in February 1937, are: D. R. Yarnall, nominated by The American Society of Mechanical Engineers to serve as trustee to succeed E. R. Fish; G. D. Barron, nominated by the American Institute of Mining and Metallurgical Engineers to succeed H. C. Bellinger; W. H. Fulweiler, nominated by The American Society of Mechanical Engineers, to succeed D. R. Yarnall; W. I. Slichter (A'00, F'12, national treasurer, and past vice-president) by the A.I.E.E. to succeed himself. Other members of the Engineering Foundation's board elected at this meeting are R. M. Roosevelt, trustee to succeed G. D. Barron of the American Institute of Mining and Metallurgical Engineers; and H. V. Coes, *ex-officio*, president of United Engineering Trustees, Inc. Other members of the Engineering Foundation's board holding over from previous election are: A. S. Tuttle, H. P. Charlesworth (M'22, F'28, and junior past-president), G. W. Fuller, O. E. Hovey, E. DeGolyer, A. E. White, C. E. Skinner (A'99, F'12, and past-president), G. G. Crawford, E. R. Fish, and J. V. N. Dorr.

An outline of the organization and objects of The Engineering Foundation is given in a companion article in this section of this issue.

Annual Report Issued by Engineering Foundation

In the annual report of The Engineering Foundation submitted by George W. Fuller chairman for 1933, and by Dr. A. D. Flinn, director, the following brief summary of activities during 1933 was given:

"Activities in 1933 included, with others, investigations of concrete and reinforced concrete arches, earths and foundations, steel columns for bridges and buildings, arch dams, and plastic properties of concrete, in the civil engineering field; critical review of the world's literature on alloy iron and alloy steels since 1890, and mining and strata research, both sponsored by the American Institute of Mining and Metallurgical Engineers; in coöperation with committees of The American Society of Mechanical Engineers, studies of boiler feed water, a critical pressure steam boiler, effects of temperature on properties of metals, cutting of metals, lubrication, cottonseed processing, and wire rope; under sponsorship of the American Institute of Electrical Engineers, 2 electric welding researches, one on pure iron electrodes and the other on nitrogen in welds.

"Assistance was given also to summer schools for engineering teachers, studies of objective types of tests for entrance to engineering colleges and other uses, vocational guidance in relation to engineering; to Engineers' Council for Professional Development, coördination committee of engineering societies, the library fund committee, Personnel Research Federation, and lecture courses for disengaged engineers.

"Reports can be found in the publications of the societies and in other journals to be seen in the offices of the societies, in Engineering Societies Library or in other libraries.

Throughout the recent years of financial difficulty, progress on the enterprises to which the Foundation has been contributing, although reduced, has been well maintained considering the handicaps. Already the signs for the future are encouraging. For coöperation and for opportunities to be helpful the Foundation expresses appreciation."

Annual Report Issued by United Engineering Trustees, Inc.

IN THE annual report of United Engineering Trustees, Inc., for 1933, it is pointed out that properties for which the corporation is responsible (real estate at cost, "funds" at book value, and library as appraised) total approximately $4,000,000. The corporation closed the year without deficit, by close economy, but for the library this is achieved only with the aid of special contributions.

Table I—Summary of 1933 Financial Report

Operation of Building		
Gross Operating Revenue	$94,770.21	
Less Operating Expenditures	93,719.42	
Net Operating Revenue	1,050.79	
Transfer of Revenue to Depreciation and Renewal Fund	0.00	
Appropriation from General Reserve Fund	3,934.40	
Total	4,985.19	
Loan written off	1,700.00	
Remainder	3,285.19	
Credit Balance in Activity Account Jan. 1, 1933	9,990.89	
Credit Balance in Activity Account Dec. 31, 1933		$13,276.08
Operation of Library		
Maintenance Revenue	$41,262.35	
Maintenance Expenditures	40,606.05	
Credit Balance for year 1933	656.30	
Transferred to Search Bureau	155.22	
Net Credit Balance for year 1933	501.08	
Credit Balance from previous year	2,921.11	
Credit Balance Dec. 31, 1933		3,422.19
Service Bureau Revenue	8,903.50	
Service Bureau Expenditures and Adjustments	10,135.27	
Debit Balance	1,231.77	
Transferred from Library	155.22	
Debit Balance for year 1933	1,076.55	
Credit Balance from previous years	1,076.55	0.00
Total net operating credit balance cumulated to December 31, 1933		$16,698.27
Funds and Property		
Funds held by U.E.T., Inc., Dec. 31, 1933 (book value)		
Henry R. Towne Eng. Fund		$49,243.13
*Combined Fund:		
Depreciation and Renewal	$331,458.03	
General Reserve	0.00	
Engineering Foundation	783,049.13	
Library Endowment	174,544.32	
Edward Dean Adams	100,000.00	1,389,051.48
Real Estate, cost to Dec. 31, 1933		1,987,793.92
Operating Cash: On Deposit	$11,467.04	
Petty Cash	250.00	11,717.04
Accounts Receivable		6,836.04
Fire Insurance Reserve		1,444.48
Due from John Fritz Medal Fund Corp.		12.85
Library as appraised for fire insurance		480,800.00
Total		$3,926,898.94
John Fritz Medal Fund (Custodian)		3,500.00
		$3,930,398.94

* A group of funds managed as if one for convenience and economy in investment transactions.

In this report it is pointed out that United Engineering Trustees, Inc., continues to be treasurer and accountant for the Professional Engineers Committee on Unemployment of the New York–New Jersey metropolitan district; and for a national relief fund; also custodian of funds for the John Fritz Medal Fund Corporation.

Among numerous other activities of the year, the flag of the 11th Engineers, American Expeditionary Forces, was committed to the care of United Engineering Trustees, Inc., in June 1933, with impressive ceremonies, by Mrs. William Barclay Parsons, widow of General Parsons, who had been colonel of the regiment.

A summary of the account's financial report for the administrative department for 1933 appears in Table I. In a companion article in this section of this issue, an outline of the organization and objects of United Engineering Trustees is given.

Election of United Engineering Trustees, Inc., Held

At the annual meeting of the United Engineering Trustees, Inc., which was held January 26, 1934, officers to serve for the year 1934 were elected. H. V. Coes, representing The American Society of Mechanical Engineers, was reëlected president. G. L. Knight (A'11, F'17), representing the A.I.E.E., was elected vice-president, as was H. P. Charlesworth (M'22, F'28, and junior past-president) also a representative of the A.I.E.E. Dr. A. D. Flinn was elected to continue as secretary, and C. P. Hunt to continue as treasurer. A. S. Tuttle was elected to continue as assistant treasurer.

Appointments to the board of trustees for the 3-year term expiring January 1937, were announced to be as follows: J. P. Hogan (M'31), H. G. Moulton, D. R. Yarnall, and H. R. Woodrow (A'12, F'23). Mr. Woodrow is the representative of the A.I.E.E. Other members of the board of trustees for the year 1934 (the first 4 having terms expiring in 1935, and the last 4 having terms expiring in 1936), are as follows: A. S. Tuttle, R. M. Roosevelt, W. L. Batt, and G. L. Knight (A'11, F'17), C. W. Hudson, W. H. Bassett, H. V. Coes, and H. P. Charlesworth (M'22, F'28, and junior past-president).

An outline of the organization and objects of United Engineering Trustees, Inc., is given in a companion article in this section in this issue.

Home Study Course in Air Conditioning Analyzed. The advantages of a home study course have been brought out by an analysis made by the officials of Rutgers University, New Brunswick, N. J. The course analyzed was in air conditioning, technical training in this subject being given to an adult group by the university extension division. Students from 36 states and 5 foreign countries were registered. It was found that former education seems to have little correlation with the degree of effectiveness with which a student acquires both the fundamental and advanced principles of air conditioning. The majority of students are employees of public utility companies, and range from executives to mechanics. The group has been able to maintain an average performance rating of slightly more than 90 per cent. The course shows a remarkably high percentage of completions, and the students in this course received grades among the highest 3 groups in all home study courses offered by the university.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Limiting Reactances of 2-Terminal Reactance Arms

To the Editor:

Texts on circuit theory show that all irreduceable 2-terminal pure reactance arms of a given number of elements may be divided into 2 distinct groups. Any arm will be potentially equivalent to all other arms in its own group and potentially inverse to all arms of the other groups. Furthermore, any such arm, having n elements, will have n-1 finite resonant and anti-resonant frequencies. Also, the reactance must be either zero or negative infinity at zero frequency and must be either zero or plus infinity at infinite frequency. If we know the number of elements and the reactance at either zero or infinite frequency we can symbolically sketch the reactance curve.

There are 2 methods of determining these limiting reactances without the use of mathematics. These 2 methods are simple and direct, and yet they seem not to have been mentioned in the literature.

To find the reactance at zero frequency, inspect the arm for a d-c path. If there is a d-c path the reactance will be zero, if not it will be a negative infinity. A d-c path between terminals can only exist through a chain of inductance elements, all of which will have zero reactance at zero frequency.

To find the reactance at infinite frequency, inspect the arm for a direct capacity path. If such a path exists, the arm will have zero reactance at infinite frequency; if not, the reactance will be a plus infinity. If a path can be traced between terminals, traversing only capacity elements and broken by no inductance elements, the reactance of each capacity element, hence of the total path, will be zero at infinite frequency.

These methods can be easily and rapidly applied to the most complicated reactance arms and serve as a valuable check on the mathematical calculation of the reactance curve. They may also be used to detect possibilities of reduction in supposedly irreduceable arms. For example, suppose an arm had an even number of elements but the above tests showed the limiting reactances to be opposites, one zero and one infinite. This would immediately indicate that somewhere in the arm there were 2 or more elements which could be combined without changing the type of reactance curve.

Very truly yours,

S. G. LUTZ (ENROLLED STUDENT)
(Purdue University, Lafayette, Ind.)

Early Development of the Transformer

To the Editor:

In the abstract of the address "A Century of Development in Industry and Engineering" given by the writer before Section M (engineering) of the American Association for the Advancement of Science, Chicago, Ill., June 27, 1933, and published in the October 1933 issue of ELECTRICAL ENGINEERING, p. 666–71, the following statement appears:

"The use of alternating current for other than local electric lighting purposes was not visualized until the serious development of the transformer took place. In 1882 Gaulard and Gibbs developed a power transformer, which invention was exploited by Westinghouse, who was quick to perceive the possibilities of the transformer in connection with long distance transmission."

I would like to add to this the following statement:

"In 1884 a transformer, which for the first time embodied a closed iron core and thus became suitable for economical practical employment in power distribution by means of alternating current, on which the whole of modern electrical engineering is based, was built by the Ganz Company of Hungary under the Zipernowsky-Déri-Bláthy patents. By 1886 such transformers were operating in a number of power stations in Europe and South America. The Ganz Company can thus claim to be the pioneers in modern power distribution by means of alternating current."

Very truly yours,

A. P. M. FLEMING (M'14)

(Local Hon. Secy. A.I.E.E.; and Director and Manager of Research and Educational Depts., Metropolitan-Vickers Electrical Co., Ltd., Manchester, England)

Personal Items

PHILIP SPORN (A'20, M'26, F'30) for the past year chief engineer of the American Gas and Electric Company, New York, N. Y., has been appointed vice-president in charge of engineering. Mr. Sporn, after receiving the degree of electrical engineer from Columbia University, spent 2 years in the testing department of the Crocker Wheeler Electric Manufacturing Company. Following this he did some postgraduate work at Columbia, and then spent one year with the Consumers Power Company, Jackson, Mich., on station and substation design, joining the American Gas and Electric Company in 1920. Since that time his promotion has been rapid. In 1920 he was made assistant to the electrical engineer. In 1921 he was also given the added responsibility of handling relay engineering for the company, and in 1922 station design was added to these other duties. In 1923 he was placed in active charge of the electrical engineering department. After directing the engineering division of the electrical engineering and construction departments he was promoted to chief electrical engineer, and last year was appointed chief engineer in charge of both the electrical and mechanical engineering activities of the American Gas and Electric Company and its subsidiaries. Mr. Sporn has been active in the A.I.E.E., the Edison Electric Institute, and the Association of Edison Illuminating Companies, as a member and chairman of a number of technical committees and subcommittees. He has contributed many papers and discussions to the A.I.E.E. in addition to his activities on its committees. Mr. Sporn is also a member of the Franklin Institute and Sigma Xi, and a fellow of the American Association for the Advancement of Science.

PHILIP SPORN

EDGAR KOBAK (A'21, M'22) vice-president and general sales manager, McGraw-Hill Publishing Company, Inc., New York, N. Y., has resigned. Mr. Kobak has been associated with this organization for the past 18 years, having been a vice-president of the company since 1926. Mr. Kobak, widely known in the electrical industry as a result of his diversified activities for the organization in the course of his rise from subscription representative to vice-president has not yet announced his future plans. He early contributed to the progress of the *Electrical World*, published by the McGraw-Hill Company, both as an editor and advertising salesman. After 2 years as an assistant editor, he joined the advertising and business division, and as a salesman for *Electrical World* and *Electrical Merchandising* covered the Chicago territory for 2 years. He spent one year in St. Louis, Mo., in a similar capacity. Upon his return to the New York headquarters of the publishing company, Mr. Kobak acted as promotion manager for *Electrical World* before becoming a vice-president in the McGraw-Hill Company. He was a member of the executive committee and of the board of directors. Mr. Kobak is president of the Advertising Federation of America. Prior to entering the publishing business, he was associated with the Georgia Railway and Power Company.

C. A. MAYO (A'13) assistant manager, The Eastern Massachusetts Electric Company, Salem, Mass., has been appointed manager of this company. In 1911 Mr. Mayo joined the Charles H. Tenney organization, entering the meter department of the Malden (Mass.) Electric Company at that time. He was superintendent of the Peoples Gas and Electric Company, Oswego, N. Y., for 3 years and from 1916 to 1931 was electrical engineer of the Malden company. The Eastern Massachusetts company, of which he is now manager, is the wholesaling and interconnecting organization of the Tenney properties north of Boston, and is now a part of the New England Power Association.

L. V. BEWLEY (A'27) engineer in the power transformer department of the General Electric Company, Pittsfield, Mass., has received one of the awards of The Charles A. Coffin Foundation for "a revolutionary new mathematical theory which greatly aids engineers in safeguarding transmission lines from lighting." Mr. Bewley is a frequent contributor of articles to the A.I.E.E. The Charles A. Coffin Foundation has been making awards each year since 1922, when it was established by the board of directors of the General Electric Company as a tribute to the late Charles Albert Coffin, founder of the company and its first president.

F. B. JEWETT (A'03, F'12), and past-president) vice-president, American Telephone and Telegraph Company, and president, Bell Telephone Laboratories, Inc., New York, N. Y., was elected a member of the board of trustees of the Carnegie Institution of Washington, D. C., at its annual meeting on December 15, 1933. Doctor Jewett has also been named by the Federal Transportation Coördinator as the chairman of the scientific research committee which will make a survey to determine "whether railroads are securing the maximum benefits from the utilization of modern science and invention."

T. M. HUNTER (A'15, M'28) engineer and sales manager, American Transformer Company, Newark, N. J., has been elected president of that organization. Mr. Hunter has been connected with the American Transformer Company for 20 years, and has been intimately identified with many of its various activities. After holding the position of manager of the industrial division of the company for several years, he was made general sales manager in 1933. Since 1929 he also has been a vice-president.

L. W. ROBERT, JR. (A'31) who for a number of years has been president of Robert and Company, Inc., consulting engineers and architects of Atlanta, Ga., and who, as announced in ELECTRICAL ENGINEERING for July 1933, p. 515, was appointed assistant secretary of the treasury in charge of public buildings about a year ago, has been removed from supervision of public building construction to the U.S. Bureau of Engraving and Printing and the Mint.

P. J. KENT (A'19) who has been chief system operator of the Edison Electric Illuminating Company of Boston, Mass., for many years, and has had 47 years of service with that company, retired from active service March 1, 1934. Mr. Kent is widely known in the eastern central station field for his activities in connection with the New England System Operators Club and for his handling of local and interchange facilities in eastern Massachusetts.

J. H. FERRY (A'20) chief engineer, Potomac Electric Power Company, Washington, D. C., was recently appointed vice-president of that organization. Mr. Ferry has been with the Potomac Electric Power Company since 1906, progressing through various positions in the engineering department and finally becoming chief engineer, a position which he still retains. He is a past-chairman of the Washington, D. C., Section of the Institute.

F. M. CLARK (A'24) physicist in the laboratory of the Pittsfield (Mass.) works of the General Electric Company, has received one of the Charles A. Coffin Foundation awards for "his development of pyranol, a non-inflammable and non-explosive liquid used as a substitute for oil in the insulation of transformers." Mr. Clark previously received an award from the Charles A. Coffin Foundation in 1931.

J. A. DARLING (A'21) assistant chief system operator, Edison Electric Illuminating Company of Boston, Mass., has been appointed chief system operator of the company, succeeding P. J. Kent (A'19). Mr. Darling entered the company's employ in 1902, becoming a load dispatcher in 1914. Three years later he was made assistant chief system operator.

S. R. Bergman (A'04) consulting engineer at the river works of the General Electric Company, West Lynn, Mass., is the recipient of one of the Charles A. Coffin Foundation awards for devising a new type of bucket manufactured by the General Electric Company for rayon manufacturers, which has banished previous failures in this piece of equipment."

E. J. Doyle (M'30) has resigned as president of the Commonwealth Edison Company, Chicago, Ill. He has served the Edison company for 38 years, having begun as Samuel Insull's office boy. It is stated that Mr. Doyle will perform, without title, his former duties, the position of president remaining unfilled.

Vannevar Bush (A'15, F'24) vice-president of Massachusetts Institute of Technology, Cambridge, and dean of engineering of that institution, has been appointed assistant treasurer. Brief biographical sketches of Doctor Bush, who has long been active in the Institute, were published in Electrical Engineering for April 1932, p. 286, and September 1932, p. 672–3.

T. C. Clark (M'27) sales engineer, W. N. Matthews Corporation, St. Louis, Mo., has recently been elected a vice-president of the James R. Kearney Corporation, St. Louis. Mr. Clark was for 13 years engaged on system operation with the Union Electric Light and Power Company of St. Louis, where his last position was division superintendent of overhead construction.

H. A. Morss (A'11, M'11) treasurer and recently-elected president of the Simplex Wire and Cable Company, Cambridge, Mass., has been appointed acting treasurer of the Massachusetts Institute of Technology, Cambridge. He has been a life member of the corporation since 1914, and assistant treasurer for many years.

R. W. Lamar (A'15) formerly general manager of the Tennessee Public Service Company, Knoxville, has been elected vice-president of that company. Mr. Lamar entered the public utility business upon graduation from Washington University, St. Louis, Mo., in 1907.

P. J. Myler (A'07) president of the Canadian Westinghouse Company, Hamilton, Ontario, Can., has been elected chairman of the company to succeed the late H. H. Westinghouse. Mr. Myler also will retain the presidency of the company.

B. S. Rodey, Jr. (A'22, M'26) assistant auditor, United Electric Light and Power Company, New York, N. Y., was recently appointed auditor of this company. Mr. Rodey also holds an identical position with the New York Edison Company.

Mark Eldredge (A'14, M'20, F'33) chief engineer, Memphis Power and Light Company, Memphis, Tenn., has been elected president of the Memphis Engineers' Club for the year 1934.

D. C. Barnes (A'04, M'20) vice-president of the Engineers Public Service Company, New York, N. Y., has resigned this office to become vice-president of the Stone and Webster Engineering Service Corporation.

F. D. Weber (A'09, M'30) chief electrical engineer, Oregon Insurance Rating Bureau, Portland, has been elected president of the Electric Club of Portland for the year 1934.

Obituary

William States Lee (A'04, M'05, F'13, and past-president), vice-president and chief engineer, Duke Power Company, Charlotte, N. C.; president of W. S. Lee Engineering Corporation of New York, N. Y., and Charlotte; and past-president of American Engineering Council, died March 24, 1934. News of Mr. Lee's death was received as this issue was going to press. A biographical sketch of Mr. Lee is scheduled for inclusion in the May 1934 issue of Electrical Engineering, as one of the group of sketches on the past-presidents of the Institute.

William Joseph Hammer (A'87, M'87, F'12, life member, past vice-president), consulting electrical engineer, New York, N. Y., and an early associate of Thomas A. Edison, died March 24, 1934. As notice of his death was received as this issue was going to press, a biographical sketch of Mr. Hammer is scheduled for inclusion in the May issue.

George Owen Squier (A'91, F'19, and member for life) retired, major-general, U.S. Army, Washington, D. C., died March 24, 1934. As notice of his death was received as this issue was going to press, a biographical sketch of Major-General Squier is scheduled for inclusion in the May issue.

Walter D'Arcy Ryan (A'02) for many years head of the illuminating laboratory of the General Electric Company, Schenectady, N. Y., and since June 1932, consulting engineer for the company, died at Schenectady, March 14, 1934. He was born at Kentville, Nova Scotia in 1870. Following private instruction, he attended Memramcoock College, in New Brunswick, and King's County Academy, Kentville, Nova Scotia. He then spent 3 years at the Royal School of Cavalry at Quebec. After a 5-year commission with the 18th Hussars, Royal Engineering, he subsequently came to the United States, and in 1891 accepted a position in the Lynn, Mass., works of the Thomson-Houston Electric Company, which subsequently became the General Electric Company. In 1896 he was promoted to the position of superintendent of test men in the West Lynn works of the General Electric Company, and shortly after this was made a commercial engineer and served as secretary of the Lynn factory committee. In 1903, he was formally designated illuminating engineer, and became one of the pioneers in this field. He was subsequently transferred to research, and was placed in charge of the commercial engineering department which is stated to have developed under his supervision to the first illuminating engineering laboratory in the world. In 1908, when the company organized the lighting laboratory in Schenectady, Mr. Ryan was given supervision of this laboratory. Here he started a series of experiments which, to a large measure, are responsible for present-day methods of floodlighting. In 1932 he was made a consulting engineer, being a consultant for the illuminating engineering laboratory. Mr. Ryan's engineering tendencies were early observed, when, in 1885, at the age of 15, he invented an ice velocipede, and 2 years later invented a rotary valve steam engine. In 1890 he developed and constructed a $^1/_2$-hp d-c motor and other small electrical devices. It was these tendencies which directed his interest to the Thomson-Houston Company at Lynn. Among the many famous striking floodlighting effects which were worked out under his direction were those for the Pan-American Exposition at Buffalo, N. Y., in 1901, the St. Louis Exposition in 1904, the Hudson-Fulton Exposition in New York City in 1909, the Panama-Pacific International Exposition in San Francisco, Calif., in 1915, and finally the Century of Progress Exposition in Chicago, Ill., in 1933. The exterior lighting for this latter exposition was designed by a corps of engineers from different companies all working under his direction. Many other lighting exhibits in this and foreign countries were designed by him, and he was frequently called upon to arrange illuminating effects for special occasions. Mr. Ryan was a charter member of the Society of Illuminating Engineers and was active in its affairs.

George Marshall Yorke (A'02, F'29) vice-president in charge of engineering, Western Union Telegraph Company, New York, N. Y., died March 18, 1934. He was born at Lowell, Mass., in 1870. In 1893 he graduated from Massachusetts Institute of Technology, Cambridge, with the degree of B.S. in E.E. From 1893 to 1911 he was employed by the American Telephone and Telegraph Company, spending the first year at Boston as inspector, the second at New York in a similar position, the third at Philadelphia, Pa., as district inspector, and the next 2 years, terminating in 1898, at Chicago as district inspector. The next year he was again at Boston, as district inspector, and in 1899 was transferred to New York as assistant electrician. He subsequently became assistant general superintendent of plant for the company, being the assistant in charge of construction engineering for the long lines department of the company. During the latter part of the period terminating in 1911, he had charge of the design of long distance central offices and of such special undertakings as the first long distance underground conduit and cable systems of the company, between New York and Philadelphia, and other points. In 1911 he became associated with the Western Union Telegraph Company at

New York, as an engineer, being appointed general superintendent of plant in 1913. In 1916 he was elected a vice-president of the company, holding this position until the time of his death. During this period he has been in charge of the engineering work of the company, including the design of all parts of the physical property, and the development of many new devices and methods in relation to both land and ocean cable telephony. Mr. Yorke was a director of the following companies: American District Telegraph Company (N. J.), Gold and Stock Telegraph Company, Stock Quotation Telegraph Company, and Teleregister Corporation. In 1918 he was appointed a member of the operating board of the U.S. Telegraph and Telephone Administration. He was a major in the Signal Officers Reserve Corps, being attached to the staff of the chief signal officer of the army, 1917–18. He was a member of the Franklin Institute of Philadelphia, the Technology Club of New York City, and the Metropolitan Museum of Art, American Museum of Natural History, and the New York Zoological Society, all of New York. He also was a member of the Machinery Club and the City Club, of New York, and the Manasquan River Golf and Country Club.

Harry Thomas Edgar (A'03, M'28) who had been division manager for Stone and Webster, Inc., Boston, Mass., for many years, died February 15, 1934. He was born at Griggstown, N. J., in 1869. Following 2 years spent in a lawyer's office at New Brunswick, N. J., he entered the employ of the Edison Electric Illuminating Company at New Brunswick in 1886 as office boy and night switchboard operator. Between 1886 and 1893 he was engaged in the installation of electrical apparatus in central stations throughout the country, and for the Edison Electric Light Company (now the General Electric Company), in New York, N. Y. From 1893 to 1897 he was secretary and general manager of the Georgia Electric Light Company at Atlanta. From 1897 to 1899 he was engaged in selling arc lamps, incandescent lamps, and carbon lamps in New England and New York. Since 1899, his work was entirely executive, managing properties under the executive management of Stone and Webster, Inc. From 1899 to 1901 he was manager of the Lowell (Mass.) Electric Light Corporation, and from 1901 to 1905 held a similar position with the El Paso (Texas) Electric Railway Company. In 1905 he became vice-president and manager of the Northern Texas Traction Company at Fort Worth, holding this position until 1910 when he became manager of the Seattle (Wash.) Electric Company. In 1912 he became district manager and division manager in charge of groups of properties under the executive management of Stone and Webster, Inc., with headquarters in Boston, holding this position for many years. Mr. Edgar was a brother of the late Charles L. Edgar (A'96, F'12) president and general manager of the Edison Electric Illuminating Company of Boston, and was an uncle of L. L. Edgar (A'12) first vice-president of the Edison company.

Norman Nelson Ross (A'93, M'94, F'12 and member for life) district turbine specialist, General Electric Company, Cleveland, Ohio, died November 1933. He was born at Washington, D. C., in 1869. He was educated principally by private tutors, and studied mechanical engineering and physics. His first position was that of telegraph operator. After serving in this position for about 2 years he was employed by the Bell Telephone Company on instruments and construction work for about 2 years, following which he was in business on his account in Montreal, Quebec, doing general electrical work for about $1^1/_2$ years. He next entered the employ of the Edison company in the works of E. Chanteloup, Montreal. He then went to the Royal Electric Company, subsequently going to Sherbrooke, Quebec, with A. J. Lawson, building Edison apparatus. After a few years in business for himself and in teaching, he reëntered the employ of the Canadian Edison Manufacturing Company at Sherbrooke, being in charge of the testing departments. After a period as foreman of construction, installing lighting in railway plants in different localities, he became district engineer for the district from Port Arthur, Ontario, to the Pacific Coast, for the company, which subsequently became the Canadian General Electric Company. Following this, Mr. Ross held other positions with this company and with the General Electric Company in United States, subsequently becoming district steam turbine specialist for the General Electric Company at Cleveland. At one time he was district steam turbine specialist in the Cincinnati, Ohio, office of the General Electric Company.

Ernest Charles Joho (A'26) telephone equipment engineer, Bell Telephone Laboratories, Inc., New York, N. Y., died December 7, 1933. He was born at Elizabeth, N. J., in 1894. His technical education was acquired through the Western Electric Company. Following one year with the Weston Electrical Instrument Company, Waverly, N. J., he entered the engineering department of the Western Electric Company at New York, N. Y., in 1913. He remained with this organization and its successor company, the Bell Telephone Laboratories, Inc., until the time of his death. For the Western Electric Company he was at first in the drafting division of the telephone system development department engaged on the design of equipment for semi-mechanical telephone offices and panel machine switching telephone offices. He was then in the engineering division of the telephone systems development department as equipment engineer on panel machine switching systems, and subsequently as resident engineer on trial installations for new type equipment at Paterson, N. J. Upon the organization of the Bell Telephone Laboratories, Inc., in 1925, he became telephone equipment engineer in the telephone systems development department. In 1917 he left the Western Electric Company for a period of military service, being reinstated in 1919. As a sargeant in Company C of the 104th Field Signal Batallion, he took part in engagements at Haute Allschut and Meus-Argonne, where he was gassed and suffered a shrapnel wound.

Maurice Grunfield (A'20) assistant chief electrical draftsman, Brooklyn Edison Company, Inc., Brooklyn, N. Y., died January 8, 1934. He was born in Roumania in 1887. He was a graduate electrical engineer from the University of Lille (France). From 1912 to 1915 he was electrical engineer, estimating and designing power plants with the Roumanian branch of Brown, Boveri and Company, Switzerland. From 1915 to 1917 he was designing draftsman on electric generators and motors for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. From 1917 to 1919 he was electrical draftsman on power stations and substations for the Interborough Rapid Transit Company, New York, N. Y. From 1919 to 1920 he was electrical draftsman, designing power stations, for Dwight P. Robinson and Company, New York. Subsequently, Mr. Grunfield joined the organization of the Brooklyn Edison Company, Inc.

William Wallace Ker (A'95 and member for life) instructor in physics and electricity at the Hebrew Technical Institute, New York, N. Y., died February 15, 1934. Two days before his death he had been teaching as usual at the institute, where he had served since 1887. Mr. Ker is said to have been one of the first instructors in the United States who established a laboratory course in electricity for boys of high school age. For several years, he was a lecturer on electricity in the public school evening lecture course for adults at New York, talking to a total of more than a million persons. His lectures were always profusely illustrated by practical experiments.

Membership

Recommended for Transfer

The board of examiners, at its meeting held February 28, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Ferris, Livingston P., asst. protection devpmt. engr., Am. Tel. & Tel. Co., New York.
Hansen, Klaus L., cons. engr., Harnischfeger Corp., Milwaukee, Wis.

To Grade of Member

Bosch, Lester L., E.E., Columbia Engg. Corp., Cincinnati, Ohio.
Boura, Felix G., asst. substation design engr., West Penn Pwr. Co., Pittsburgh, Pa.
Brown, Richard E., prof. of E.E., New York Univ., New York.
Esterline, John W., pres., The Esterline-Angus Co. Indianapolis, Ind.
Henderson, S. L., section engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Keenan, Henry B., engr., Wairarapa Elec. Pwr. Board, Carterton, New Zealand.

Kent, Paul N., distribution engr., Kansas City Pwr. & Lt. Co., Kansas City, Mo.
Linville, Thomas M., motor and generator engg. dept., Gen. Elec. Co., Schenectady, N. Y.
Lusignan, Joseph T., Jr., chief E.E., Ohio Brass Co., Barberton, Ohio.
Miller, Ralph H., supervisor—technical staff—systems devpmt. dept., Bell Tel. Labs., Inc., New York.
Oesterlein, Wm. J., chief E.E., Harnischfeger Corp., Milwaukee, Wis.
Rankin, Harry C., lab. engr., New England Pwr. Engg. and Serv. Corp., Providence, R. I.
Spence, Payton W., elec. engr. in research, Am. Tel. & Tel. Co., New York.
Tuck, H. P., lecturer in E.E., Univ. of Tasmania, Hobart, Tasmania, Australia.
Welman, Douglas P., director and general mgr., Messrs. Aretz, Ltd., London, Eng.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before April 30, 1934, or June 30, 1934, if the applicant resides outside of the United States or Canada.

Adams, A. W., 7316 Jones Ave., N. W., Seattle, Wash.
Alvarez, R. J., N. Y. Edison Co., N. Y. City.
Amorosi, G. J., 337 E. 63 St., Shrub Oak, N. Y.
Anderson, B. T., Harnischfeger Corp., Milwaukee, Wis.
Anderson, G. C., Gen. Elec. Co., Schenectady, N. Y.
Anderson, T. R., U.S. Coast & Geodetic Survey, Seattle, Wash.
Anderson, T. V., Bristol Silver Mines Co., Pioche, Nev.
Anderson, W. A., Pub. Serv. Commission of N. H., Manchester, N. H.
Andrews, J. G., Glidden Co., Cleveland, Ohio.
Ashman, K. W., Intl. Business Machines Corp., Endicott, N. Y.
Atkinson, L. G., Jr., Westinghouse Elec. & Mfg. Co., Wilkinsburg, Pa.
Baker, E. G., Aristocrat Mfg. Co. Ltd., Toronto, Ont., Can.
Barber, W. H., Buffalo, Gen. Elec. Co., Buffalo, N. Y.
Bardet, P. E., Interboro Rapid Transit, N. Y. City.
Best, R. A., 497 7 Ave., Troy, N. Y.
Blake, R. W., N. Y. State Elec. & Gas Co., Endicott, N. Y.
Blasen, R. E., 607 New Post Office Bldg., Portland, Ore.
Bonstein, H. L., Jr., 1046 Washington St., Easton, Pa.
Boyle, F. B., Jr., 50 Highview Ave., Melrose, Mass.
Brady, L., 406 South 2 St., Las Vegas, Nev.
Brainin, S., 2022 Lexington Ave., N. Y. City.
Butler, A. E., Indiana Bell Tel. Co., Indianapolis.
Chapman, R. E., 1 Arnold Ave., Toronto 9, Can.
Chennault, W. S., Western Union Telegraph Co., Sweetwater, Texas.
Clark, F., Westinghouse Lamp Co., Bloomfield, N. J.
Coakley, J. J., Central R.R. Co. of N. J., Jersey City.
Cohen, A. B., 211 Washington St., Dorchester, Mass.
Coleman, L. L., Okla. Gas & Elec. Co., Oklahoma City.
Collins, H. McD., 1117 Harvard Rd., Crafton, Pa.
Collins, J. D., Pub. Serv. Elec. & Gas Co., Elizabeth, N. J.
Collins, O. B., 6719 McCune Ave., St. Louis, Mo.
Comins, A. W., RCA Radiotron Co., Harrison, N. J.
Congelosi, R. A., Globar Corp., Niagara Falls, N. Y.
Constant, E. S., Okla. Gas & Elec. Co., Oklahoma City.
Cripps, R. H., Harman-Pacific Co., Los Angeles, Calif.
Cummings, G. A., Westinghouse Elec. & Mfg. Co., E. Springfield, Mass.
Darmody, P. A., 520 21 St., Cairo, Ill.
Dibble, C. H. (Member), Corning Glass Works, Corning, N. Y.
Ding, A. P., U. S. Engineers Corp., Portland, Ore.
Eimert, F. J., Mass. Inst. of Tech., Cambridge.
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Fink, G. R., Gen. Elec. Co., Schenectady, N. Y.
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Guiles, W. L., Tomlinson Bros., New Haven, Conn.
Hagenbuch, L. G., Jr., Gibbs & Hill, N. Y. City.
Hale, W. L., Jenkins Music Co., Kansas City, Mo.
Harris, W. N., Portland Gen. Elec. Co., Portland, Ore.
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Howles, E. J., N. Y. Edison Co., N. Y. City.
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Long, H. E. (Member), Conn. Pwr. Co., New London.
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McCollum, T. A., Okla. Gas & Elec. Co., Enid.
McDermott, W. M., Gen. Elec. Co., Milwaukee, Wis.
McFarland, J. L., Radio Station WEXL, Royal Oak, Mich.
McGreer, T. H., Clarno, Ore.
McIntire, R. L., Okla. Gas & Elec. Co., Chandler.
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Smith, S. G., National Tube Co., Ellwood City, Pa.
Speer, D. S., McCann & Co., Pittsburgh, Pa.
Spelman, I. L., United Elec. Lt. & Pwr. Co., N. Y. City.
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Tucker, W. H., W. W. & C. F. Tucker, Inc., Hartford, Conn.
Vasso, J. W., Am. Brass, Torrington, Conn.
Virostek, J. S., Lower Main St., E. Douglas, Mass.
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Werts, E. W., C. A. Dunham Co., Marshalltown, Iowa.
Wilkerson, S. C., Aluminum Co. of Am., Calderwood, Tenn.
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Wolfe, H. C., Wilmington, N. Y.
Wolff, A. E., Cities Ice Cream Co., Aurora, Ill.
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Woodward, J. S., Gen. Elec. Co., Schenectady N. Y.
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Yorton, S. C., 39 Third St., Camden, N. Y.
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Young, N. F., Okla. Gas & Elec. Co., Oklahoma City.
Ziev, M., Easton Car & Constr. Co., Easton, Pa.

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Foreign

Ambor, C. J., Cia Carbonifera y de Fundicion Schwager Coronel, Chile, S. A.
Austin, D. R., c/o Hong Kong & Shanghai Banking Corp., Shanghai, China.
Bogdanoff, A. K., Teploelectro Project, (T. E. P.) Moscow, U. S. S. R.
Christoff, E. C., 92 Tzar Samouil. Sofia, Bulgaria.
Fukasawa, S., 944 5 Chome, Inetsuka-Machi, Oji-ku, Tokio City, Japan.
Lan, H. A., China Motor Bus Co., Ltd., Hong Kong, China.
Logan, A., Corporation of Aylesbury Electricity Dept., Aylesbury, Buckinghamshire, Eng.
Nagano, F. M., Hawaiian Elec. Co., Honolulu, T. H.
Pillai, P. R., Indian Inst. of Science, Bangalore, India.
Raman, R. V., M/s S. T. Sons & Co., Trinchinopoly, South India.
Ramaswamy, B. S., Indian Inst. of Science, Bangalore, India.
Wadthekar, S. V., Arrah Elec. Supply Co., Ltd., Arrah (Bihar & Orrissa), India.

12 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Bonell, R. K., 45 Clinton St., Newark, N. J.
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Dean, George H., Corrie, Old Shoreham Road, Shoreham-by-Sea, Eng.
Garvey, Fred A., 4144 Cottage Grove, Chicago, Ill.
Gentilini, Celso, 1512 Wood St., Wilkinsburg, Pa.
Griffith, Geo. M., R. no. 1, Tucker, Ga.
How, John H., 42 Wai Oi Road East, Canton, China.
Mathisen, Karsten V., 912 Noyes St., Evanston, Ill.
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Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during January are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface or text of the book in question.

HILFSBUCH für EINKAUF und ABNAHME METALLISCHER WERKSTOFFE. By E. Pohl. Berlin, VDI-Verlag, 1933. 142 p., illus., 8x6 in., cloth, 8 rm. Describes the properties of commercial metals and alloys which affect their suitability for various uses, and indicates the best methods of testing and of writing specifications for purchase. The work is intended as a reference book for the purchaser, especially the small buyer.

PHYSICS of ELECTRON TUBES. By L. R. Koller. N. Y. & Lond., McGraw-Hill Book Co., 1934. 205 p., illus., 9x6 in., cloth, $3.00. The fundamental phenomena involved in the operation of electron tubes are explained in this work, which discusses what takes place within the tube rather than circuits that contain them, or their applications. The book is based upon lectures at the Massachusetts Institute of Technology and is intended for engineers and students of physics.

MANUAL of STRUCTURAL DESIGN. By J. Singleton. Topeka, Kansas, H. M. Ives & Sons, 1933. 196 p., illus., 10x7 in., lea., $4.50. Aims to provide, in one volume, all the information required to solve ordinary problems relating both to structural steel and reinforced concrete. It is intended for the practical engineer, conversant with the theory of structural design.

POWER SUPPLY ECONOMICS. By J. D. Justin and W. G. Mervine. N. Y., John Wiley & Sons, 1934. 276 p., illus., 9x6 in., cloth, $3.50. Discusses load predictions, the internal economics of steam-electric and hydroelectric plants and the cost of power from each, peak-load plants, oil-engine plants, purchased power and similar topics; setting forth the general economic principles which govern the selection of the best solution.

SYMPOSIUM on CAST IRON, held at Joint Meeting of the Am. Foundrymen's Assn. and the Am. Soc. for Testing Materials. Phila., Am. Soc. for Testing Materials, 1933. 164 p., illus., 9x6 in., paper, $1.00; cloth, $1.25. The purpose of this symposium is to provide concise, authoritative information upon the composition, metallurgy, properties and uses of the many grades of cast iron now available. Sections are devoted to the metallurgy, properties, classification and specifications, heat treatment and welding of cast iron, as well as one to factors in casting design which are important.

TABLES of INTEGRALS and OTHER MATHEMATICAL DATA. By H. B. Dwight. N. Y., Macmillan Co., 1934. 222 p., illus., 9x6 in., cloth, $1.50. A useful collection of derivatives and integrals of the more important functions, accompanied by a selection of tables of numerical values and provided with an adequate index. The book is clearly printed and of convenient size, and adapted to the needs of college students.

TASCHENBUCH für FERNMELDETECHNIKER. By H. W. Goetsch. 5 ed. Munich & Berlin, R. Oldenbourg, 1933. 600 p., illus., 8x5 in., cloth, 14.50 rm. Especially designed as a reference book for telegraph and telephone engineers. In addition to telegraphic and telephonic communication over wires, it also discusses other electrical methods of signalling used in railway work, mining, clock circuits, telemetering, etc. Revised and enlarged.

TECHNISCHE AKUSTIK, Pt. 1 (Handbuch der Experimentalphysik, Band 17, Pt. 2). By E. Waetzmann and others; ed. by W. Wien and F. Harms. Leipzig, Akademische Verlagsgesellschaft, 1934. 538 p., illus., 10x7 in., cloth, 44 rm. The first of 2 volumes upon applied acoustics, intended to give a comprehensive review of the field. This volume contains chapters on the underlying mechanical and electrical concepts, on acoustic measurement, the microphone, telephone, and loud speaker, on the propagation of sound in free media and on architectural acoustics.

TECHNISCHE AKUSTIK, Pt. 2. (Handbuch der Experimentalphysik, Band 17, Pt. 3). By E. Waetzmann and others; ed. by W. Wien and F. Harms. Leipzig, Akademische Verlagsgesellschaft, 1934. 434 p., illus., 10x7 in., cloth, 36 rm. The prevention of noise and vibration, medical acoustics, musical instruments, sound transmission by radio, the phonograph and phonautograph, and the talking film are discussed in the present instalment of this treatise.

Die TECHNOLOGIE des EDELSTAHLES, Aufbau, Verwendung, Herstellung, Behandlung, Prüfung und Fehler des Edelstahles. By A. Kropf. Halle (Saale), Wilhelm Knapp, 1934. 264 p., illus., 9x6 in., paper, 12.80 rm. The characteristics of the various alloy steels are described and methods of manufacturing, working, and heat treating are discussed. Methods of testing are given, with the standard specifications of England, Germany, Switzerland, and the United States. One chapter is devoted to flaws and their origins. Special attention is given to practical questions.

Die WIRTSCHAFTLICHE AUSGESTALTUNG STÄDTISCHER DREHSTROMNETZE. By W. v. Mangoldt. Berlin, Julius Springer, 1933. 76 p., illus., 10x7 in., paper, 5.50 rm. A discussion of the engineering and economic factors of the design of the a c distribution systems. Methods are given for determining the cable cross section, the most favorable transmission voltage and the number and sizes of the transformer stations in the system. A critical comparison of the most popular systems of distribution is included and the conditions to which each is best suited are explained.

AMERICAN SOCIETY for TESTING MATERIALS. PROCEEDINGS, 36th Annual Meeting, Chicago, Ill., June 26–30, 1933. V. 33, Pts. 1 & 2. Phila., A.S.T.M., 1933. Pt. 1, 1092 p.; Pt. 2, 804 p., illus., 9x6 in., paper, $5.50. Contain the reports of the various committees, new and revised tentative standards, tentative revisions of current standards, and the technical papers presented at the meeting. These include a lecture by Dr. H. J. Gough, a symposium on cast iron, and numerous papers on the testing of metals, cement, concrete, and other materials.

APPLIED GEOPHYSICS in the SEARCH for MINERALS. By A. S. Eve and D. A. Keys. 2 ed. Cambridge, Eng., Univ. Press; N. Y., Macmillan Co., 1933. 296 p., illus., 9x6 in., cloth, $4.25. Supplies a readable account of the theory and practice of the various methods of geophysical prospecting, with some critical appraisal of them, based upon field experience. The new edition has been revised and brought up to date. A bibliography is included.

BILDWORT ENGLISCH, Technische Sprachhefte, Heft 6: CABLE and WIRELESS COMMUNICATION. Berlin, V.D.I.-Verlag, 1933. 33 p., diagrs., 8x6 in., paper, 1.50 rm. The sixth pamphlet of this series provides a practical course in the terminology of telegraph and telephone engineering for the foreign engineer who wishes to read English technical works. The usual technical words are explained by drawings. An English-German glossary is included.

CHEMICAL ENGINEERS' HANDBOOK (Chemical Engineering Series). Ed. by J. H. Perry and W. S. Calcott. N. Y. and Lond. McGraw-Hill Book Co., 1934. 2609 p., illus., 7x5 in., lea., $9.00. A convenient, practical reference book for chemical engineers, as well as plant executives, mechanical engineers, and others engaged in manufacturing. The field covered includes not only chemical engineering but also the important related fields. Special attention is given to cost data.

CONJUGATE FUNCTIONS for ENGINEERS, a Simple Exposition of the Schwarz-Christoffel Transformation Applied to the Solution of Problems Involving Two-Dimensional Fields of Force and Flux. By M. Walker. Lond., Humphrey Milford; N. Y., Oxford Univ. Press, 1933. 116 p., illus., 10x6 in., cloth, $4.75. A simple exposition of the Schwarz-Christoffel transformation, intended for engineers who have to deal with problems in hydrodynamics and aerodynamics, electrostatics and electromagnetism. The subject is presented from the point of view of the engineer, rather than the mathematician, and developed through a number of typical practical examples.

COST and PRODUCTION HANDBOOK. Edit. by L. P. Alford. N. Y., Ronald Press Co., 1934. 1544 p., illus., 8x5 in., lea., $7.50. A reference work for industrial managers, which endeavors to provide, in one volume, all the information usually needed in the administration and operation of industrial concerns. Budgeting, factory organization, production planning and control, purchasing, storekeeping, job standardization, rate setting, incentive plans, buildings and machinery, costs, cost accounting, depreciation, labor, and other topics are treated.

DEPRECIATION, a Review of Legal and Accounting Problems by the Staff of the Public Service Commission of Wisconsin. Submitted to the Nat. Assn. of R. R. and Utilities Commissioners at its 45th annual convention in Cincinnati, Ohio, October 11, 1933. N. Y., State Law Reporting Co., 1933. 196 p., illus, 9x6 in., paper, $1.50; cloth, $1.85. This report, prepared at the request of the National Association of Railroad and Utilities Commissioners, presents the view of the Wisconsin Public Service Commission as to the depreciation policy which should ultimately be adopted, and discusses some of the outstanding problems and legal principles that confront commissions.

HAUSHALT - KÄLTEMASCHINEN und KLEINGEWERBLICHE KÜHLANLAGEN. By R. Plank and J. Kuprianoff. 2 ed. Berlin, J. Springer, 1934. 182 p., illus., 10x6 in., cloth, 13.20 rm. The development of mechanical refrigerators for domestic and shop use is described comprehensively, with full attention to American, as well as European practice. Details are given of the construction and method of working of the compressors, condensers and other components of most of the systems of commercial importance.

Engineering Societies Library

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MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Meter Devices Co. Expands.—Due to the rapid growth of its business, the Meter Devices Co. has found it necessary to move into a new factory and offices at 1001 Prospect Ave., S.W., Canton, Ohio. In addition to meter test switches and test blocks, the company also produces a complete line of meter accessories and devices.

New Indicating Cutout.—The L. S. Brach Mfg. Corp., Newark, N. J., has announced a new line of porcelain plug and cartridge cutouts which have neon lamp indicators built in permanently, and known as Fuse-O-Lite indicating cutouts. When a fuse fails, a neon lamp glows, indicating the position of the blown fuse; inserting a new fuse puts out the light.

New Fuses.—The Jefferson Electric Co., Bellwood, Ill., has developed a new line of super-lag fuses, incorporating a design principle that prevents failure of the fuse until the current overload has continued for a sufficient space of time to be dangerous. These renewable fuses are made in all standard ratings, both knife-blade and ferrule types.

New Heavy Duty Receptacle.—The Delta-Star Electric Co., Chicago, has developed a new, heavy duty, multi-contact receptacle for use in connection with metal-clad switchgear and control equipment. The receptacle can be bolted flat against an opening in metal housings enclosing the control wiring, thus giving a direct connection with minimum space requirements. It is made in 3, 4, 5, 6, or 7 poles and all except the three pole are polarized.

Wolverine Tube Co. Appoints Agents.—The J. T. Hill Sales Company, Los Angeles, has been appointed by the Wolverine Tube Co., Detroit, as agent for the Wolverine line of electrical soldering lugs, consisting of standard and automotive types of every size, single and double splicing sleeves for overhead work and split-tinned sleeves for underground work. W. H. Beaven, Birmingham, has been appointed to represent the company in a tier of southern states.

Special Flashlight.—A new flashlight case designed especially for heavy service and work around transmission lines, bus bars or other electrical circuits has been introduced by the Bond Electrical Corp., Jersey City, N. J. Known as the Bond "Voltpruf," the flashlight is heavily insulated for protection against high voltages. The heavy ribbed fiber case is designed to withstand severe service. The new flashlight is available in both focusing spotlight and spreadlight types.

Trade Literature

Mica.—Bulletin, 24 pp. Describes "Micabond," a bonded mica insulating material. It is supplied in punched and formed parts, sheets, tubes, etc. Continental-Diamond Fibre Co., Newark, Del.

Brewery Equipment.—Bulletin 149-A, 16 pp. Describes equipment for the power, electrical, pumping, and other requirements of the brewing industry. Allis-Chalmers Mfg. Co., Milwaukee.

Shafting.—Booklet, 16 pp. Describes production and characteristics of cold finished and other types of shafting. Union Drawn Steel Co., Massillon, O.

Converters.—Bulletin 509-A, 4 pp. Describes construction, operation and uses of various types of frequency converters. Bulletin 502-B describes inverted rotary converters. The Louis Allis Co., Milwaukee.

Illumination.—Bulletin SP-1989, 32 pp. Outstanding developments in illumination are illustrated, including flood lighting, bridge and street lighting, industrial and aviation field lighting, etc. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Cable Installation.—Bulletin, 12 pp., "Installing General Cable Trenchlay." Covers the recommended methods for the handling and protection of all types of low-voltage, trenchlay (non-metallic sheathed) cables. General Cable Corp., 420 Lexington Ave., New York.

Mining Locomotives.—Bulletin D.M.F. 5550, 4 pp. Describes Baldwin Westinghouse mining locomotives. Bulletin D. M. F. 5544 describes Baldwin Westinghouse permissible storage battery locomotives. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Bakelite.—Bulletin, 48 pp., "Bakelite Molded." Describes Bakelite molding materials and their innumerable uses, including electrical and allied applications, and outlines the molding process and necessary equipment. Profusely illustrated. Bakelite Corp., Bound Brook, N. J.

Electrical Equipment for Railroads.—Catalog 1966, 60 pp. This catalog on electrical equipment for railroad shops and maintenance of way describes apparatus such as arc welding equipment, heat treating and melting apparatus, motors, controls, lighting, battery charging, etc. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Time Switches.—Bulletin. Describes a new series of special, self-starting, synchronous time switches in 7 different models, providing a special time control for operating temperature regulators, oil burner controls, neon signs, traffic controls, stoker, draft and machinery controls. The latest addition to the extensive line of Paragon time controls has been developed to meet the demand for a small, compact and simplified time switch at a very moderate price. Paragon Electric Co., Old Colony Bldg., Chicago.

Supervisory Control.—Bulletin C. 1983, 10 pp. Describes Westinghouse two-wire visicode and audicode supervisory control, a simplified and sure means of obtaining remote indication of apparatus units and especially applicable for railway, central station, substation and oil and gas pump line operation. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Motors.—Bulletin 1165, 16 pp. Describes bracket bearing synchronous motors. In addition to the standard line of motors for general requirements, including exciters, control equipment, etc., the bulletin also treats of special construction features, such as anti-friction bearings, enclosed collector rings, splash-proof type, enclosed fan-cooled type, and vertical motors. A discussion is included on the use of the synchronous motor for improvement of power factor with examples applying the graphical method for figuring power factor corrections. Allis-Chalmers Mfg. Co., Milwaukee.

Boiler-Feed Pumps.—Bulletin No. 2078, 6 pp. Describes Cameron Type NT multi-stage centrifugal pumps for pressures up to 600 pounds. An interesting feature of this pump is the hydraulic balance obtained by placing an equal number of impellers back to back. This results in the elimination of high-pressure stuffing boxes. Of the two stuffing boxes used, one is under second-stage pressure, the other is under suction pressure. The casing is split horizontally, allowing the entire rotor to be removed without disturbing the bearing adjustment, exposing bearings to dirt or moisture, or disconnecting any part of the piping. Ingersoll-Rand Co., 11 Broadway, New York.

New Lightning Arresters.—Improvements in both protective performance and mechanical construction have been incorporated in the new, form D Thyrite, station-type, lightning arresters of the General Electric Co., and the exclusive no-time lag feature has been continued. The impulse breakdown voltage of the 11.5-kv unit is about 40-kv crest. When applying AIEE standard surge current (1500 amp.), the impulse voltage across the arrester unit is limited to only 36-kv crest—little more than two times the crest rating of the arrester, and an improvement of 30 per cent over previous designs. The sealed construction of the series gap protects the gap elements from moisture or atmospheric influences.

The new arrester embodies unit construction, an exclusive Thyrite feature, whereby standard 11.5-kv arrester units are common to, and interchangeable in, arresters of all voltage ratings. Three-point support and bolting between units of the new arrester simplify assembly and avoid mechanical strains on porcelains. Within the unit the series gap is hermetically sealed, metal caps being bottle-cap-crimped over the ends of the porcelain container, with the gaskets permanently locked in their original compressed position, excluding moisture and making the arrester operation independent of atmospheric influence. The interior elements of the new arrester can be put readily into the unit housings of existing arresters, thereby enabling Thyrite arresters now in service to be modernized to incorporate the advanced protective performance of the new arrester and the advantages of the new sealed gap.